Numerical evaluation of the seismic response of the main typologies of non-masonry (non-URM) buildings that are found within the Groningen region

Report on soil-structure interaction (SSI) impedance functions for SDOF systems

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Eucentre

(European Centre for Training and Research in Earthquake Engineering)

Date October 2015

Editors Jan van Elk & Dirk Doornhof

General Introduction

The transfer of the ground motions resulting from an earthquake into buildings is described by the dynamic soil-structure interaction (SSI). Apart from the building typology also the foundation and the local soil conditions are important for the soil-structure interaction. This report describes the methodology for the development of the impedance functions used to capture the soil-structure interaction in the fragility curves (Ref. 1) for buildings.

Three main building typologies have been investigated; "Detached", "Terraced" and "Apartment" buildings. Both shallow and deep foundations of concrete and masonry have been considered. Different representative soil profiles have been used to capture the impact of the variability in local soil conditions (Ref. 2 to 4).

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1. Development of v2 fragility and consequence functions for the Groningen Field, H. Crowley, R. Pinho, B. Polidoro, P. Stafford, October 2015.
2. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part I, Deltares, Pauline Kruiver, Ger de Lange, Ane Wiersma, Piet Meijers, Mandy Korff, Jan Peeters, Jan Stafleu, Ronald Harting, Roula Dambrink, Freek Busschers, Jan Gunnink
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<u>Comment:</u>
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<tr><td>Assurance</td><td colspan="4">Eucentre</td></tr>
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Project Information

Project Title: **Numerical evaluation of the seismic response of the main typologies of non-masonry (non-URM) buildings that are found within the Groningen region**

Project Start: 12th May 2014

Duration: 24 months

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Deliverable Information

Deliverable Title: **Report on soil-structure interaction (SSI) impedance functions for SDOF systems**

Data of Issue: 20th October 2015

Editor(s): Roberto Nascimbene

Reviewers: Rui Pinho and Helen Crowley

REVISION: **v1**

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Introduction

This document describes the procedure for the definition of impedance functions to be used in dynamic soil-structure interaction (SSI) for fragility curves derivation, to be then employed in seismic risk assessment for the Groningen region.

Three main building typologies, namely "Detached", "Terraced" and "Apartment", were considered taking into account both shallow and deep type foundations and different materials (i.e. concrete and masonry).

For calculation of impedance functions three representative soil profiles were defined. They were obtained as the mean and mean plus and minus standard deviation of the V_S profiles measured with seismic cone penetration tests (SCPT) in the area of interest.

1 Soil-structure interaction methodology

Dynamic soil-structure interaction (SSI) denotes the coupling between the structure and its supporting medium during an earthquake. SSI can be analyzed using a direct method or sub-structure approach. For definition of fragility curves, SSI will be analyzed using a sub-structure approach, which allows splitting kinematic and inertial interaction in different sub-steps and considering their effects using the principle of superposition (see Mylonakis et al., 2006).

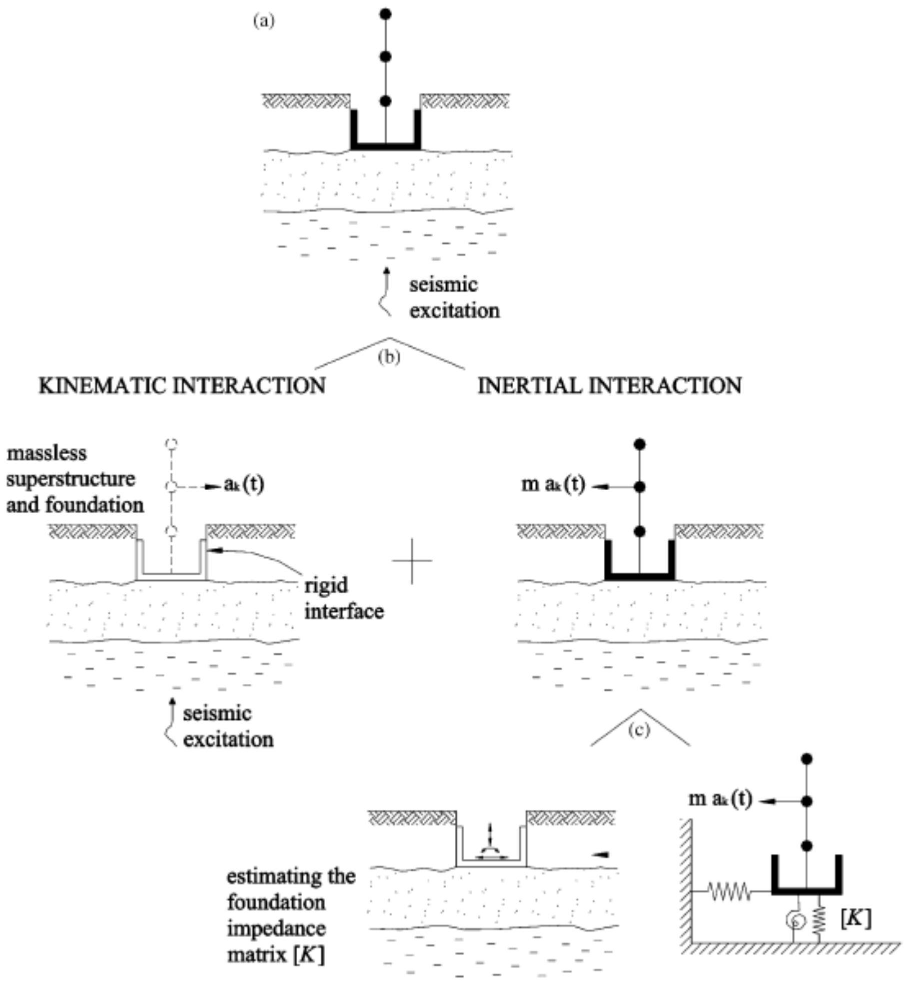


Figure 1.1: a) SSI problem; b) Decomposition into Kinematic and Inertial response; c) two step analysis for inertial interaction (from Mylonakis et al., 2006).

Kinematic interaction leads a modification of the free field motion due to the geometry and stiffness of the foundation. Kinematic interaction is mainly associated to seismic wave incoherence, which consists of spatial variation of both horizontal and vertical ground motion, and embedment effects which includes the variation of free-field ground motion with depth. The latter has significant effects on the Foundation Input Motion (FIM) generally reducing the translational motion and introducing a rotational component.

Inertial interaction includes the dynamic response of the soil-structure system and is characterized predominantly by shifting of structure frequencies to lower soil-structure frequencies and reduced response due to significant radiation damping.

1.1 Sub-structure approach

SSI analysis using the sub-structure approach will consist of the following steps:

a) Kinematic interaction;
b) Computation of the foundation impedance (i.e. dynamic stiffness);
c) Inertial interaction.

1.1.1 Kinematic interaction

This step involves the definition of the Foundation Input Motion (FIM) of the massless rigid foundations. Variation of amplitude and frequency content with depth may be considered for embedded structures, however due to the reduced embedment (absence of basement) the embedment-equivalent dimension ratio is small and the influence of the rotation induced by the embedment will be neglected in the following.

In accordance with Arup (2015a, 2015b), kinematic interaction is considered negligible on the response of the simplified model used for definition of fragility curves. The input motion for the time-history analyses will be the free-field motion which however should account for the effects of soil stratigraphy consequent of a site response analysis.

1.1.2 Computation of the foundation impedance (i.e. dynamic stiffness)

Impedance represents the force-displacement (or moment-rotation) characteristics of the soil, which for a rigid foundation entails the definition of the relation for each of the six degree of freedom, which must include also the coupling terms for embedded foundations.

Impedance functions are computed assuming a rigid foundation system, considering that the effective stiffness of the foundation (which is a function of the foundation itself and the stiffening effect of structural elements tied in the foundation) is large compared to the soil. This hypothesis involves a translational component (usually smaller than free field) and in addition contains a rotational component.

The resulting six by six matrix is complex, since it represents the stiffness and damping characteristics of the soil, and frequency dependent. The foundations impedance depends on the stratigraphy characteristics of the deposit, geometry and embedment of the foundation, material properties, etc. The frequency dependent foundations impedance will be calculated using the purposely developed numerical code DYNA6.1 briefly described in section 1.2.

1.1.3 Inertial interaction

This step involves the evaluation of the response of the coupled soil-foundation-structure system due to FIM. The coupled soil-structure system will include the structure, or its modal representation, and the soil, which will be replaced by springs and dashpots anchored at the foundation level. Because the soil-structure system will be solved using direct-integration time history analysis a frequency independent impedance value is required. The constant value of the impedance can be:

a) the static value;
b) the values at a frequency corresponding to the fundamental frequency of the combined soil-structure system;
c) the main frequency of the input signal.

1.2 Overview of the code for calculation of impedance functions

The DYNA6.1 program developed by the Geotechnical Research Centre of Western Ontario University, computes the frequency dependent stiffness and damping constant of both surface foundations, embedded foundations and piles, pile interaction in a group and other features. The program returns the response of rigid foundations to different types of dynamic loads, for rigid footings, all six degrees of freedom are considered as coupled.

The computation of impedance functions for shallow footings is evaluated using simplified approaches, which consider three categories of idealized soil profiles:

a) half-space;
b) uniform stratum on rigid base;
c) layer on top of a half-space (composite medium).

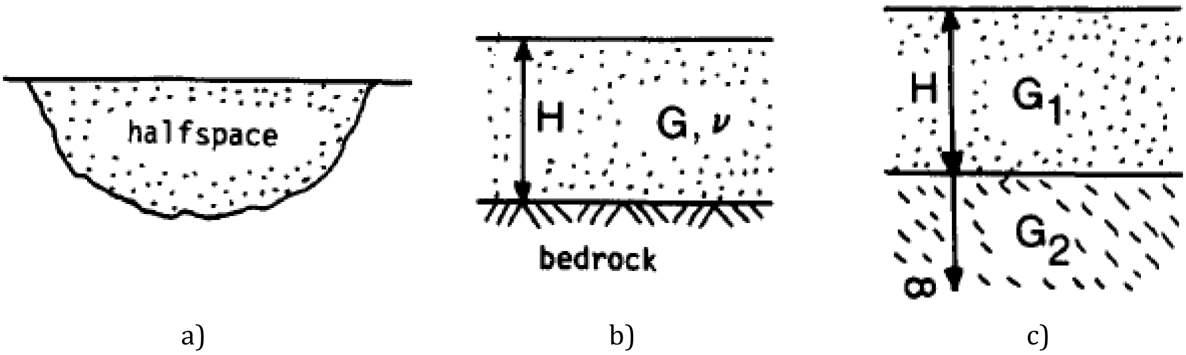


Figure 1.2: Soil profiles: a) half-space; b) uniform stratum on rigid base; c) layer on top of a half-space (from DYNA6 User's manual).

Moreover, for composite medium the soil profile can be either uniform or non-uniform in accordance with the schematization shown in Figure 1.3. These models represent a wide spectrum of actually encountered soil profiles.

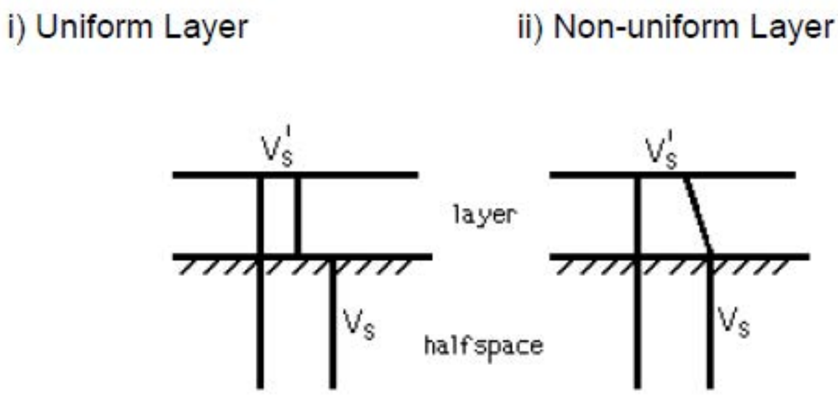


Figure 1.3: Soil velocity profile for composite medium (from DYNA6 User's manual)

For piles foundations it is possible to considered a layered medium, for each layer the following input parameters are required: thickness, shear wave velocity, soil unit weight, Poisson's ratio, damping ratio.

1.2.1 Code limitations

The code includes some limitations that shall be taken into account for definition of the input parameters. For composite medium, the impedance functions are exact for the radio of layer thickness to half-width of the square footing (H/a) equal to 0.5, 1, 2, 3 and 4 for uniform layers and equal to 2, 3, 4, 5 and 10 for non-uniform layers. If the ratio (H/a) doesn't coincide with one of the above values the program chooses the closest (H/a) ratio available, interpolation is not implemented because of the strong non-monotonic variations at high frequencies.

In the composite-medium option, accurate values of stiffness and damping are used at frequencies equal to 0.10, 0.25, 0.50..., 4.75 and 5.0 times (Vs'/a) where Vs' is the shear wave velocity at footing base level and a is half width of the square base (or the equivalent square base). For a frequency less than 0.10 Vs'/a, the program uses the minimum value (0.10 Vs'/a) and for frequencies in the range (0.10÷5.0) Vs'/a, a linear interpolation is implemented. If the frequency is greater than 5 (Vs'/a) the program uses the maximum value of 5 (Vs'/a).

For composite medium, Poisson's ratio of the half-space is assumed 0.33 in this option. Material damping of soil is assumed 0.03 and 0.05 for the layer and the half-space, respectively. Two values for Poisson's ratio of the layer are available 0.33 and 0.45. If a different value is entered the program sets it to the closest one (interpolation is not implemented in the program because of non-monotonic variations). Three values of the ratio between the shear wave velocity at footing base and at half-space are available 0.8, 0.6, and 0.3, if a different value is entered the program sets it to the closest one. The ratio of unit weight of the half-space to that of the layer is assumed 1.13.

Finally, for rectangular shallow foundations the code provide equal value of horizontal dynamic stiffness in x and y direction. In order to take into account a different value of horizontal stiffness in x and y direction for rectangular foundation, a proper scaling factor has been introduced considering the closed form solution available for homogeneous halfspace. For shallow foundations over halfspace, the static horizontal stiffness of a square foundation is:

$$K_{x,sq} = K_{y,sq} = \frac{9GL}{2-\nu} \tag{1}$$

where G is the shear modulus, ν is the Poisson's ratio and L is the half width dimension. For rectangular foundations the horizontal static stiffness is:

$$K_{y,rect} = \frac{2GL}{2-\nu}\left[2 + 2.5\left(\frac{B}{L}\right)^{0.85}\right] \tag{2}$$

$$K_{x,rect} = K_{y,rect} - \frac{0.2\,GL}{0.75-\nu}\left[1 - \frac{B}{L}\right] \tag{3}$$

where B and L half width dimensions, with L>B and oriented along the x-axis. Supposing that the code uses equivalent square shape approximation for calculation of stiffness, it is possible to consider the two ratios $\frac{K_{y,rect}}{K_{square}}$, $\frac{K_{x,rect}}{K_{square}}$ evaluated based on equations (1) to (3), to scale the horizontal stiffness output of the code, maintaining the dependence of frequency provided by the code itself.

1.2.2 Remarks on impedance functions

Negative diagonal stiffness may occur under some conditions; they are most likely to be returned for higher frequencies, rigid footings vibrating in the vertical direction particularly with soil Poisson's ratio close to 0.5, heavy single piles in weak soil or pile groups. Negative stiffness pose no problems in response calculations because the total soil resistance is a resultant of its real part, depending on stiffness, and imaginary part, depending on damping, at low frequencies, the diagonal stiffness constants are always positive.

Sometimes, sharp peaks occur in the plot of pile group stiffness versus frequency. Such peaks or valleys occur because under dynamic loads, soil motions travel from pile to pile in the form of travelling waves. As a result, and depending on frequency (wave length) and pile spacing, the pile may tend to vibrate in phase in which case the group stiffness is reduced, or in anti-phase, which increases the stiffness and leads to marked peaks.

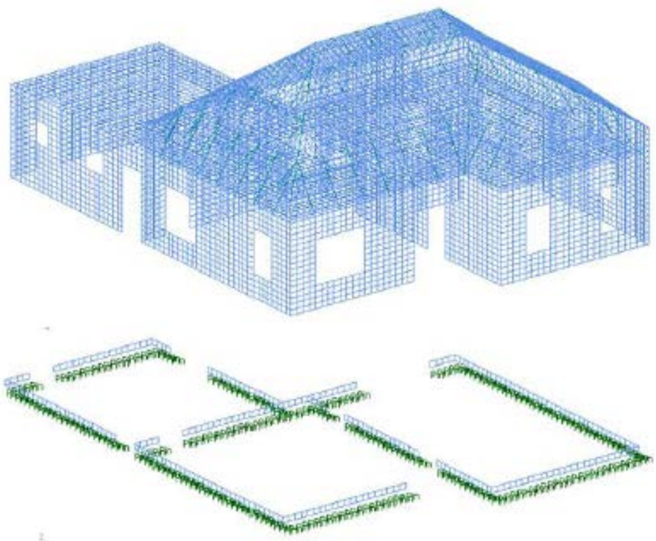
2 Identification of the building typologies

The building typologies considered for impedance functions calculation include: Detached, Terraced and Apartment building types. Table 2.1 summarizes the correspondence between the building, foundation type, material of the foundation and model considered in calculation.

Table 2.1: Building typology considered for impedance functions calculation

Building type	Foundation type	Material	Model
Detached	Shallow	Masonry	T3
Detached	Shallow	Concrete	T3
Detached	Deep	Concrete	T3
Terraced	Shallow	Concrete	Type M
Terraced	Shallow	Masonry	Type M
Terraced	Deep	Concrete	T1*
Apartment	Deep	Concrete	Farmsum

Building type "T3" is a prototype building representing a typical "detached house" in the building stock of the Groningen area; Figure 2.1 shows a 3D model and an isometric rendering building type T3. Detached house are founded both on shallow and deep foundations type. Shallow foundations have both masonry and concrete foundations. Strip footing and pile cap have 0.5 m of embedment.



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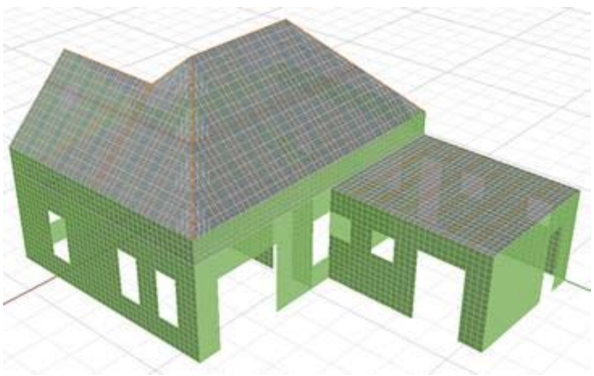


b)

Figure 2.1: Building type T3 representing a typical Detached house building: 3D model and isometric rendering (from Arup 2015a,b).

Building type "M" is a prototype building representing a single unit of typical "Terraced house" founded on shallow foundations in the building stock of the Groningen area. The cases with 2, 4, 6 and 8 units are considered for computation of impedance functions. Figure 2.2 shows a plan view of 1 unit of Building type M. Shallow foundations of Terraced house can be either of masonry or concrete material. Strip footing has 0.5 m of embedment.

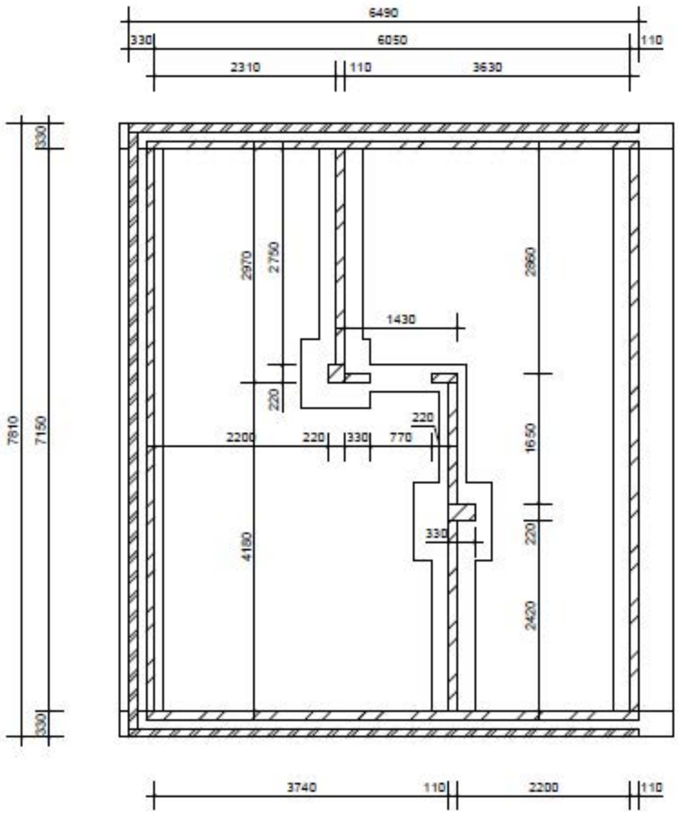


Figure 2.2: Plan view of 1 unit of Building type M representing a typical Terraced building on shallow foundations (from Zonneveld ingenieurs, 2015).

Building type "T1*" is a prototype building representing a typical "Terraced house" founded on deep foundations in the building stock of the Groningen area. The case with 4 units is considered for computation of impedance functions. Figure 2.3 shows an isometric view of Building type T1*. Footing cap has 0.5 m of embedment.

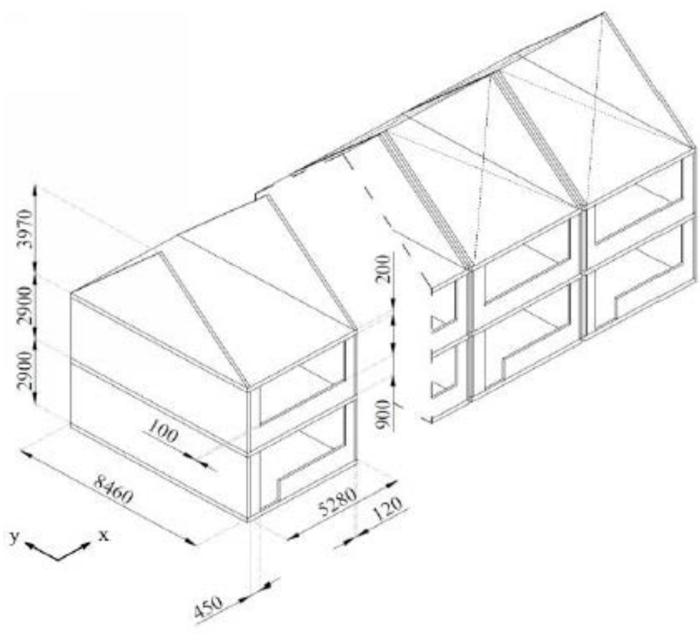


Figure 2.3: Isometric view of Building type T1* representing a typical Terraced building on deep foundations (from Arup 2015b).

The “Farmsum” building (Dijkhuis, 2015) is assumed as a prototype building representing a typical “Apartment house” in the building stock of the Groningen area. Apartment house is founded on deep foundations. Figure 2.4 shows a plan view of “Farmsum” building type. Footing cap has 0.5 m of embedment.

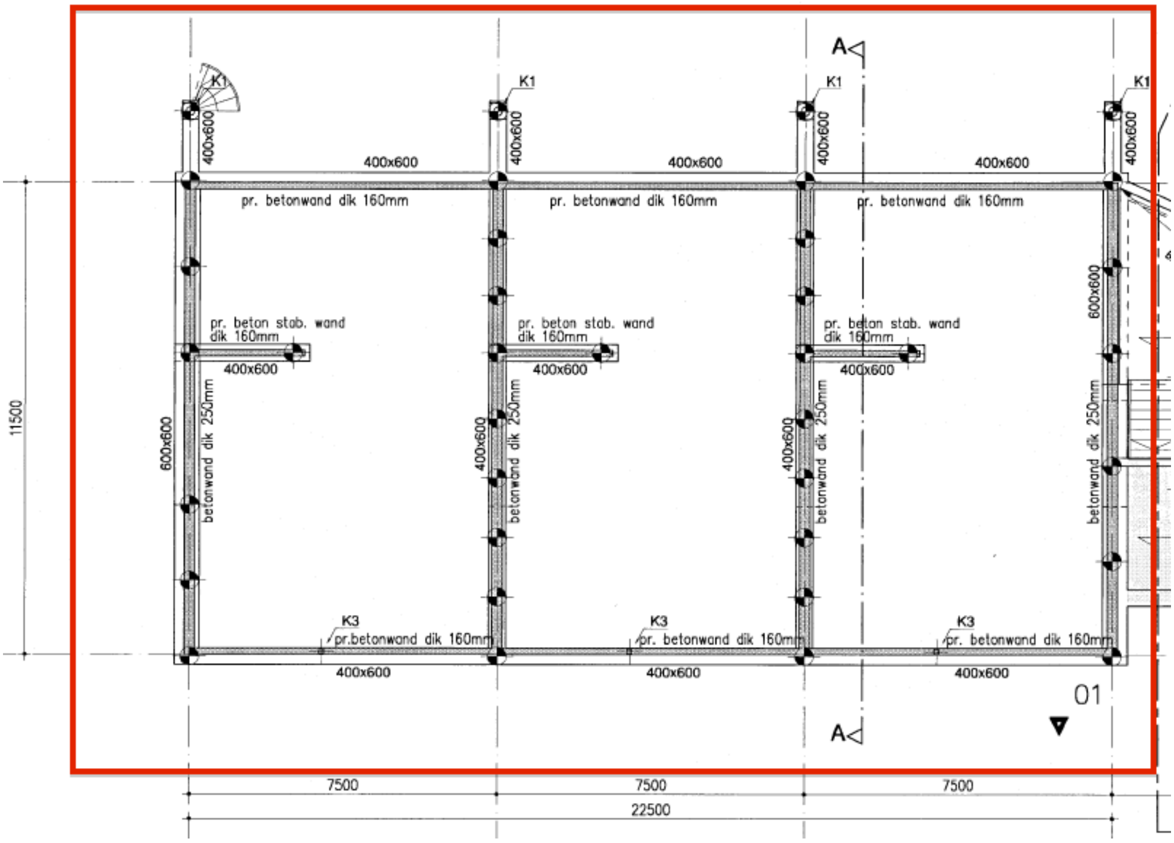


Figure 2.4: Plan view of Farmsum Building representing a typical Apartment building on deep foundations (from Dijkhuis, 2015).

2.1 Foundation types

A typical unreinforced masonry foundation (URM) is a strip foundation that is achieved by a widening of the load bearing walls to approximately 550 mm, a typical foundation section is shown in Figure 2.5. This type of foundation has been considered for both for Detached and Terraced buildings type. The inertia characteristics of the foundation have been evaluated considering, in accordance with Arup (2015a, 2015b), a square section 550mm wide, characterized by the same moment of inertia of the section showed in Figure 2.5. The resulting height of the equivalent square section is equal to 264mm.

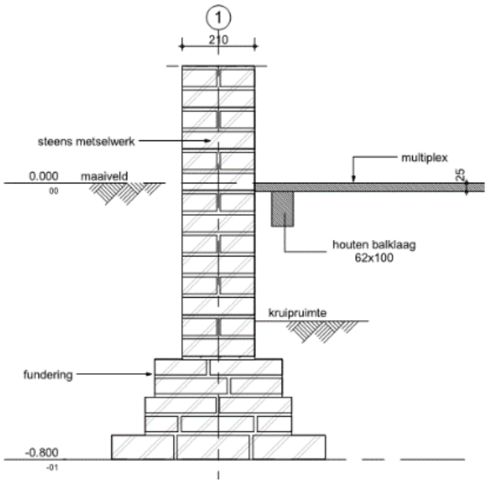


Figure 2.5: Typical masonry foundation (from Arup 2015b).

A typical reinforced concrete foundation is a strip foundation with square cross section 330mm wide (see Figure 2.6) This type of foundation has been considered for both for Detached and Terraced buildings type.

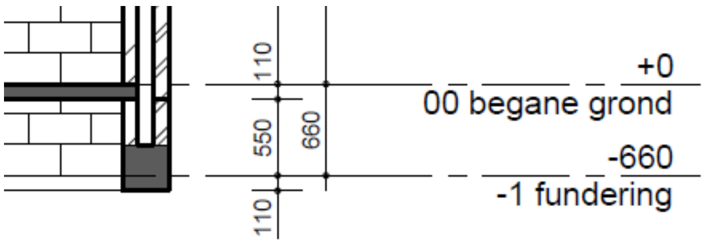


Figure 2.6: Typical concrete foundation (from Zonneveld ingenieurs, 2015).

The foundations of the building type T1* representing the Terraced type building on deep foundations consists of 250x250 mm square section concrete piles and 600x400 mm (H x W) reinforced concrete (RC) capping beams. Piles are spaced approximately 1.65m.

The deep foundations of the Apartment building type (Farmsum model) consist of 450 mm solid circular section concrete piles. The reinforced concrete (RC) capping beams are either 600x400 mm or 600x600mm (H x W). A particular of the foundation is shown in Figure 2.7.

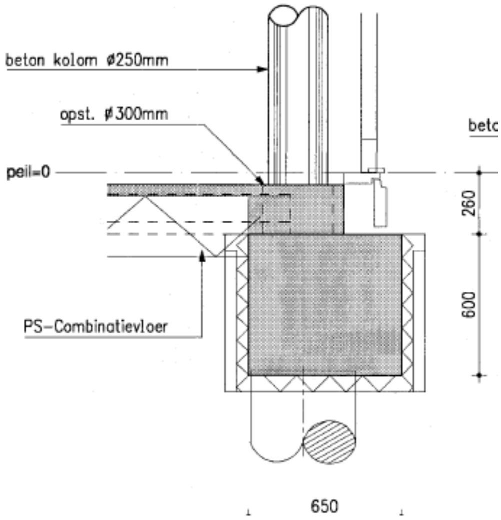


Figure 2.7: Particular of the foundation of the Apartment building type (from Zonneveld ingenieurs, 2015).

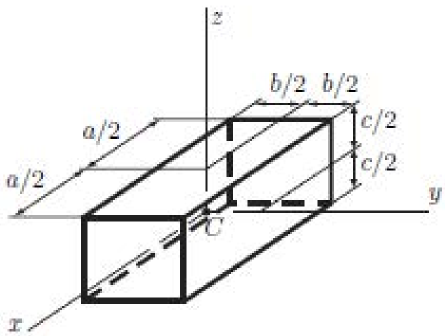
3 Steps for impedance functions calculation

The calculation of the impedance functions requires the steps listed below:

a) Computation of the global inertia of the foundation system.
b) Definition of the shear wave velocity profile.
c) Selection of the soil model.
d) Selection of soil parameters accounting for soil nonlinearity through a proper V_S scaling factor.
e) Computation of the impedance functions.

The foundations of the building considered consist of a grid of continuous beams oriented in two orthogonal directions. The structural model used for definition of the fragility curves is a single degree of freedom system in which the contact with the soil is limited to a single point. The impossibility to model the spatial distribution of the foundations requires the definition of an equivalent foundation representative of inertia and contact area of the real foundations. The computation of the global inertia of the foundation system involves the following steps:

i) Computation of the mass and center of gravity of the real foundation;
ii) Computation of the moment of inertia (I_{XX}, I_{YY}, I_{ZZ}) of each foundation beams with respect of its center of gravity (see Figure 3.1);
iii) Computation of the transportation moment and product of inertia (I_{XY}, I_{YZ}, I_{XZ}) for each beams with respect to the center of gravity of the foundation system;
iv) Computation of the moment of inertia of the whole foundation;
v) Computation of the equivalent foundation dimensions such as to maintain the contact area and the ratio between width and length equal to the real foundation.



$$m = \rho abc$$
$$I_{xx} = \frac{1}{12}m(b^2 + c^2)$$
$$I_{yy} = \frac{1}{12}m(a^2 + c^2)$$
$$I_{zz} = \frac{1}{12}m(a^2 + b^2)$$

Figure 3.1: Scheme of strip beam foundation and corresponding moment mass of inertia with respect to the centre of gravity.

4 Soil model

4.1 Shear wave velocity profiles

For a better definition of the frequency dependence of the foundations impedance functions, representative soil profiles need to be defined. This section describes the definition of reference V_S profiles for the area of interest (section 4.1.1), which are then used to evaluate the profiles for impedance functions calculation both for shallow (section 4.1.3.1) and deep (section 4.1.3.2) foundations.

4.1.1 Reference V_S profiles

The area under investigation is rather large, the zonation and the definition of reference soil profiles for the area is not yet completed. However, in the framework of fragility curves definition, it is necessary to define representative soil profiles for impedance functions calculation. In order to have a limited number of representative soil profiles able to capture the rather wide variability of the shear wave velocity profiles of the area, the results of V_S profiles obtained from seismic cone penetration tests (SCPT) (data from Deltares, 2015) has been used. The SCPT were used to characterize the shallow part of the deposit (upper 30 m) therefore are suitable for impedance functions definition. Figure 4.1 shows the V_S profiles measured by SCPT (blue lines) together with the mean (red line) and mean plus and minus the standard deviations (black lines) and the upper and lower envelop (yellow lines).

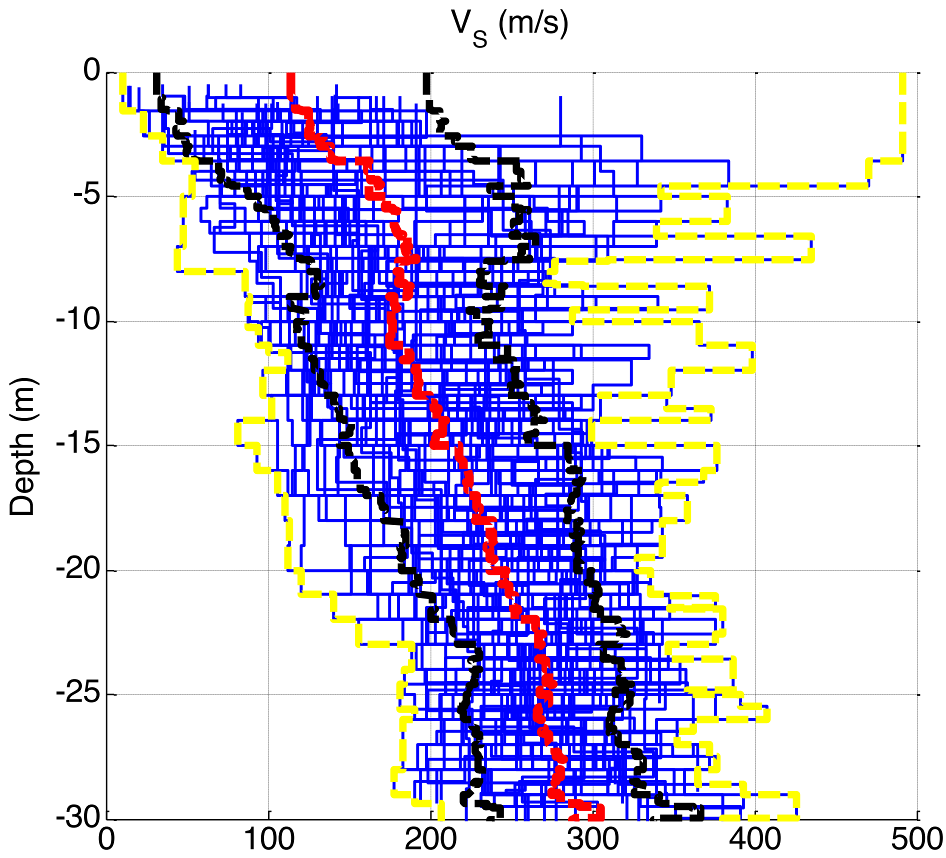


Figure 4.1: Shear wave velocity profiles obtained by SCPT in the Groningen area: Measured (blue lines); Mean (red line); Mean ± standard deviation (black lines); Upper and lower envelop (yellow lines) (data from Deltares, 2015)

For the aims of this work, three reference soil profiles have been select corresponding to the mean, mean plus and minus one standard deviation (see Figure 4.2). For each of the three reference profile the $V_{S,30}$ parameter has been computed:

- Mean $V_{S,30}$= 199m/s
- Mean - 1 std $V_{S,30}$= 113m/s
- Mean + 1 std $V_{S,30}$= 268m/s

The number of SCPT executed and their spatial distribution allows considering the three reference profiles representative and suitable for the definition of the impedance functions to be used for fragility curves definition.

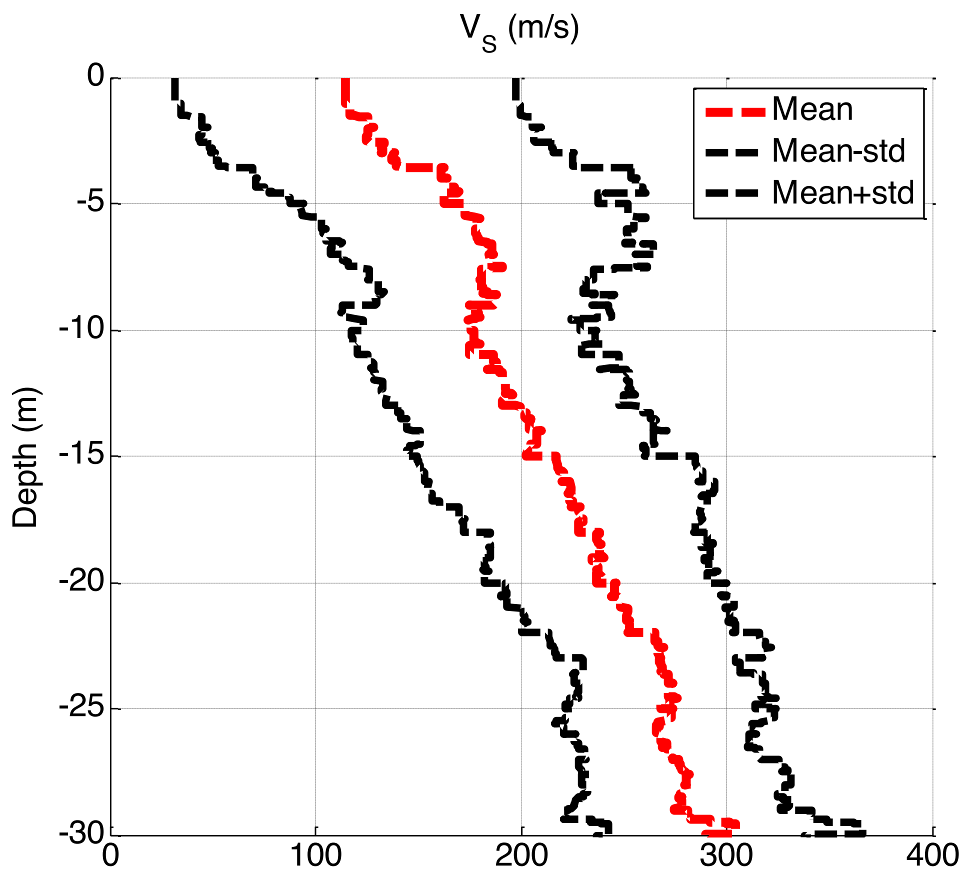


Figure 4.2: Reference shear wave velocity soil profiles for definition of impedance functions: mean (red line) and mean plus and minus standard deviation (black lines) profiles.

The shear modulus at low strain (G_{max}) can be obtained through the theory of the elasticity:

$$G_{max} = \rho \cdot V_S^2 \quad (1)$$

where ρ is the mass density assumed equal to 1900 kg/m³.

4.1.2 V_S scaling factor to account for soil non-linearity

The shear modulus is non linear because depend on the strain level reached during strong motion. Shear modulus degradation depend among other by soil type and strong motion level, to account for non linear effect in a simplified manner, elastic parameters (i.e. G or V_S) will be reduced using the reduction factors proposed by Eurocode 8-part 5 in Table 4.1 (see Figure 4.3).

Table 4.1 — Average soil damping ratios and average reduction factors (± one standard deviation) for shear wave velocity v_s and shear modulus G within 20 m depth.

Ground acceleration ratio, $\alpha.S$	Damping ratio	$\frac{v_s}{v_{s,max}}$	$\frac{G}{G_{max}}$
0,10	0,03	0,90(±0,07)	0,80(±0,10)
0,20	0,06	0,70(±0,15)	0,50(±0,20)
0,30	0,10	0,60(±0,15)	0,36(±0,20)

$v_{s,\,max}$ is the average v_s value at small strain (< 10^{-5}), not exceeding 360 m/s.

G_{max} is the average shear modulus at small strain.

NOTE Through the ± one standard deviation ranges the designer can introduce different amounts of conservatism, depending on such factors as stiffness and layering of the soil profile. Values of $v_s/v_{s,max}$ and G/G_{max} above the average could, for example, be used for stiffer profiles, and values of $v_s/v_{s,max}$ and G/G_{max} below the average could be used for softer profiles.

Figure 4.3: Table 4.1 of Eurocode 8 part 5

The three V_S reference profiles defined in section 4.1.1 have been scaled to account for strain dependence of soil stiffness (e.g. shear modulus) considering three scaling factors (SF) in accordance with EC8-part 5. For each of the three scaling factors a strong motion level has been associated, this correspondence can be eventually refined based on a site response analysis. Table 4.1 summarizes the selected scaling factors and the corresponding peak ground acceleration considered.

Table 4.1: V_S scaling factor used to account for the strain dependence of soil stiffness

Name	V_S scaling factor	Peak ground acceleration
SF1	0.90	0.10g
SF2	0.65	0.25g
SF3	0.50	0.50g

4.1.3 Soil model for calculation of impedance functions

For impedance functions calculation a soil model among the one available on the software (see section 1.2) can be selected. Based on the selected soil model, which is different for shallow and deep foundations, the reference V_S soil profile will be used to the define the input parameters taking into account the code limitations described in section 1.2.1.

4.1.3.1 Shallow foundations

The soil model selected for the computation of the impedance functions of shallow foundations is the composite medium (i.e. layer on top of half space), this model better takes into account the frequency dependence than half space model. Because the reference shear wave velocity profiles have an increment which is rather linear in the upper part, the non-uniform soil profile is preferred to the uniform in order to avoid impedance functions dominated by the main frequency of the uniform soil. Composite medium with non-uniform shear wave velocity profile is characterized by a linear shear wave velocity profile in the layer and constant value on the half space, particularly there are a set of fixed ratio between the initial shear wave velocities of the layer and half-space (see Figure 1.3).

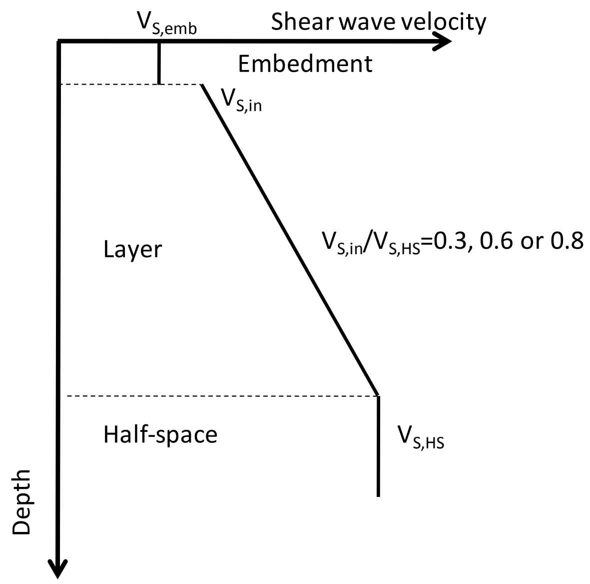


Figure 4.4: Shear wave velocity profile input parameters for composite medium.

The input parameters of the composite medium soil model have been selected through a fitting procedure which account for the fixed ratio between initial shear wave velocities of the layer and half-space. The fitting procedure involves the following step:

- Selection of the thickness of the layer;
- Linear regression of the reference V_S profile within the thickness of the layer and evaluation of $V_{S,in}^*$;
- Computation of the half space shear waves velocity ($V_{S,HS}^*$) as mean value of V_S between the bottom of the layer and depth 30m;
- For the better ratio $V_{S,in}/V_{S,HS}$=K plot of two fitting curves characterized by the following input parameters:
    - Profile 1: $V_{S,in}=V_{S,in}^*$ and $V_{S,HS}= V_{S,in}^* /K$;
    - Profile 2: $V_{S,in}=K \cdot V_{S,HS}^*$ and $V_{S,HS}= V_{S,HS}^*$;
- Selection among Profile 1 and 2 the better profile.

The selection of the thickness layer is linked to the ratio $V_{S,in}/V_{S,HS}$=K used, because K can assumes only fixed values changing the thickness layer, it is possible to improve the quality of the fitting of the reference profile. Figure 4.5 shows an example of definition of shear wave velocity profile for composite medium using the above procedure. The example shows the case of mean reference profile with the SF1 scaling factor. To have a better fit in the upper part of the deposit, which affects more the impedance functions, profile 1 has been selected for this example.

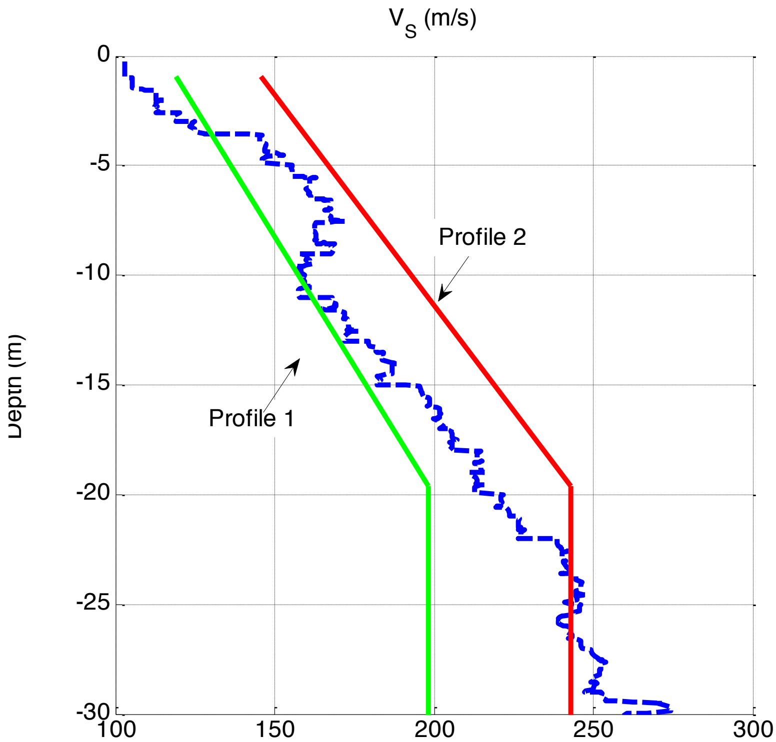


Figure 4.5: Example of shear wave velocity profile definition for composite medium.

Numerical values of the input parameters used for impedance functions calculation are summarized in Table 4.2. Figure 4.6, Figure 4.7 and Figure 4.8 show the V_S profiles used for impedance functions calculation of shallow foundations for the three reference V_S profiles defined in section 4.1.1, the figures shows only the cases with scaling factor equal to 0.9 (i.e. SF1), the other cases have similar shape with values summarized in Table 4.2.

The high water table level (at -1m) is taken into account in all calculations. For practical purposes saturated density has been considered, moreover the undrained response under dynamic condition has been considered setting up the Poisson's ratio at 0.45.

Table 4.2: Input parameters for composite medium soil model – Shallow foundations

		Embedment				Composite medium				
V_S profile	Scaling factor	γ [N/m³]	H_{emb} [m]	$V_{S,emb}$ [m/s]	ν [-]	γ [N/m³]	H_{layer} [m]	$V_{S,in}$ [m/s]	$V_{S,in}$ / $V_{S,HS}$ [-]	ν [-]
Mean	SF1	18632	0.5	103.1	0.45	18632	18.65	119.0	0.6	0.45
	SF2	18632	0.5	80.2	0.45	18632	18.65	92.5	0.6	0.45
	SF3	18632	0.5	57.3	0.45	18632	18.65	66.1	0.6	0.45
Mean – standard deviation	SF1	18632	0.5	28.4	0.45	18632	25	62.3	0.3	0.45
	SF2	18632	0.5	22.1	0.45	18632	25	48.5	0.3	0.45
	SF3	18632	0.5	15.8	0.45	18632	25	34.6	0.3	0.45
Mean + standard deviation	SF1	18632	0.5	177.7	0.45	18632	25	178.5	0.6	0.45
	SF2	18632	0.5	138.2	0.45	18632	25	138.8	0.6	0.45
	SF3	18632	0.5	98.7	0.45	18632	25	99.2	0.6	0.45

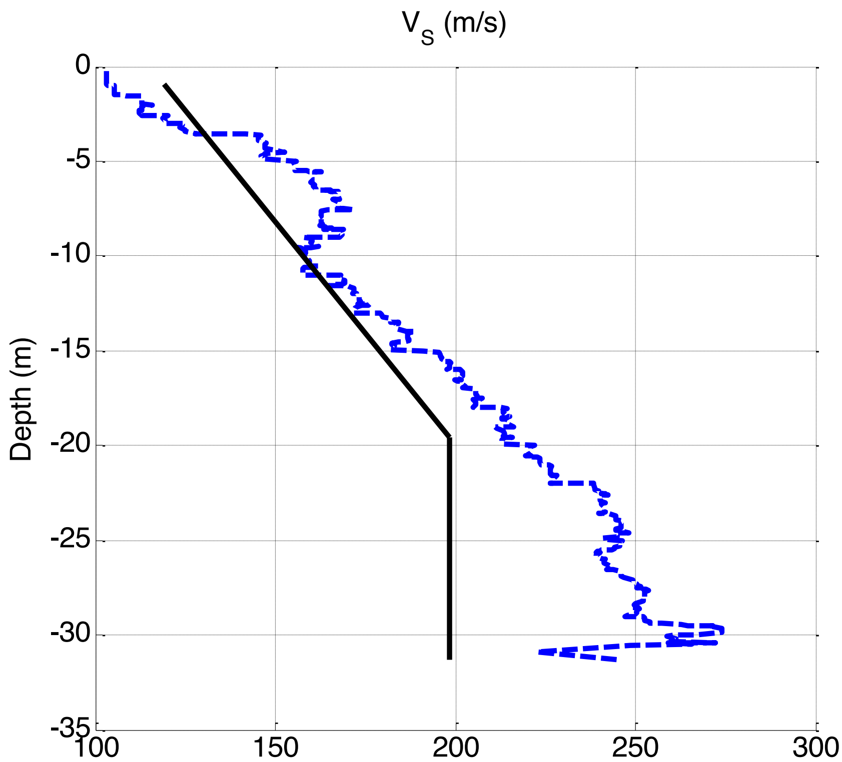


Figure 4.6: Definition of shear wave velocity profile for impedance function calculation: Mean reference profile with Scaling factor SF1 (blue lines); input profile for composite medium (black line).

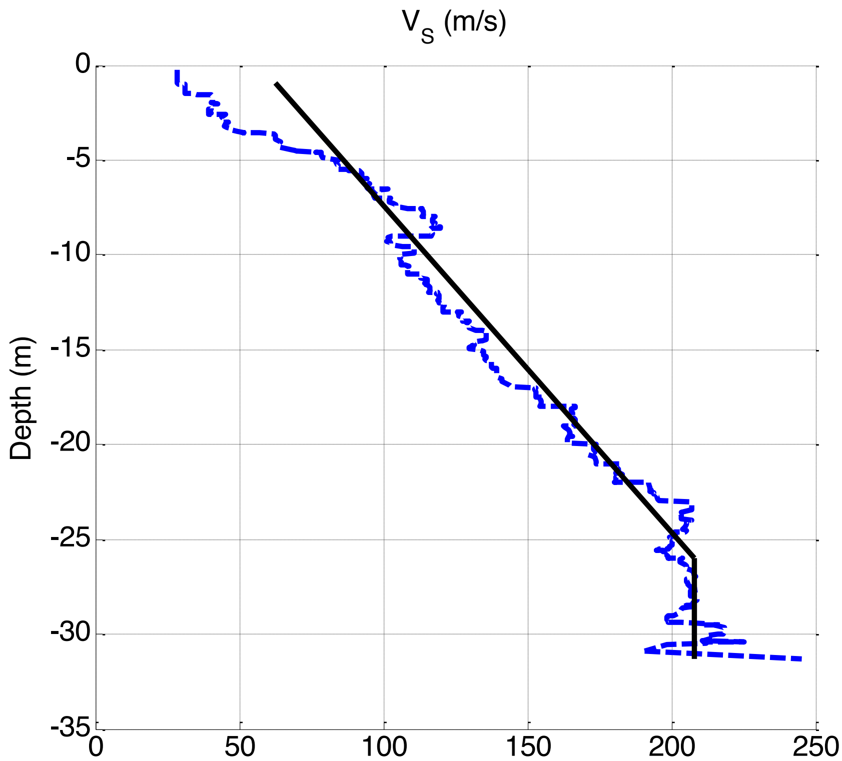


Figure 4.7: Definition of shear wave velocity profile for impedance function calculation: Mean – standard deviation reference profile with Scaling factor SF1 (blue lines); input profile for composite medium (black line).

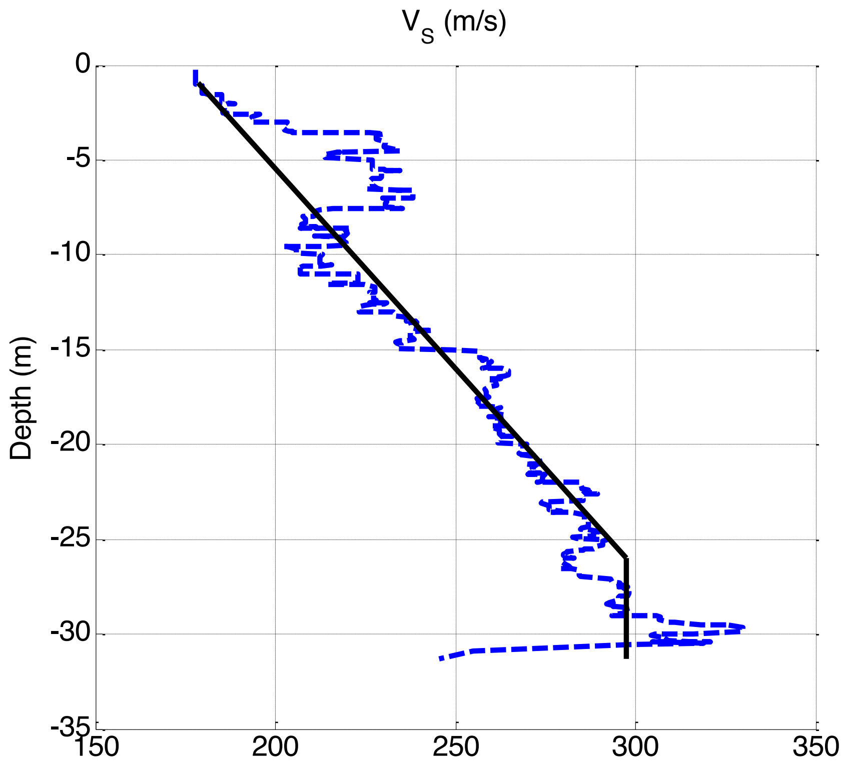


Figure 4.8: Definition of shear wave velocity profile for impedance function calculation: Mean + standard deviation reference profile with Scaling factor SF1 (blue lines); input profile for composite medium (black line).

4.1.3.2 Deep foundations

For deep foundations the code allows the use of layered medium. For each stratum the input parameters are: thickness, shear wave velocity, weight of unit volume, Poisson's coefficient and damping factor. The depth interested by the presence of piles are subdivided into three or four layers, the shear wave velocity of each layer is equal to the average value within the stratum. The thickness and shear wave velocity of the layers are summarized in Table 4.3. For the embedment the weight of unit volume is equal to 18631N/m^3 and the damping factor is equal to 0.01. For the layers and half-space the weight of unit volume is equal to 19612N/m^3 and the damping factor is equal to 0.02. Poisson's coefficient is equal to 0.45 for each layer.

The high water table level (at -1m) is taken into account in all calculations. For practical purposes saturated density has been considered, moreover the undrained response under dynamic condition has been considered setting up the Poisson's ratio at 0.45.

Table 4.3: Input parameters for layered soil model – Deep foundations

V_S profile	Scaling factor	H_{emb} [m]	H_1 [m]	H_2 [m]	H_3 [m]	H_4 [m]	$V_{S,emb}$ [m/s]	$V_{S,1}$ [m/s]	$V_{S,2}$ [m/s]	$V_{S,3}$ [m/s]	$V_{S,4}$ [m/s]	$V_{S,HS}$ [m/s]
Mean	SF1	0.5	2.8	7.4	5.8	-	103.1	115.7	160.1	183.5	-	216.2
	SF2	0.5	2.8	7.4	5.8	-	80.2	90	124.5	142.7	-	168.2
	SF3	0.5	2.8	7.4	5.8	-	57.3	64.3	88.9	101.9	-	120.1
Mean – standard deviation	SF1	0.5	3.8	8.4	3.8	-	28.4	46.7	107.4	133.9	-	172.0
	SF2	0.5	3.8	8.4	3.8	-	22.1	36.4	83.5	104.1	-	133.7
	SF3	0.5	3.8	8.4	3.8	-	15.8	26.0	59.6	74.4	-	95.5
Mean + standard deviation	SF1	0.5	2.8	4.0	3.9	5.3	177.7	190.6	228.7	213.5	240.3	260.8
	SF2	0.5	2.8	4.0	3.9	5.3	138.2	148.2	177.9	166.0	186.9	202.8
	SF3	0.5	2.8	4.0	3.9	5.3	98.7	105.9	127.0	118.6	133.5	144.9

Figure 4.9, Figure 4.10 and Figure 4.11 show the V_S profiles used for impedance functions calculation of deep foundations for the three reference V_S profiles defined in section 4.1.1, the figures shows only the cases with scaling factor equal to 0.9 (i.e. SF1).

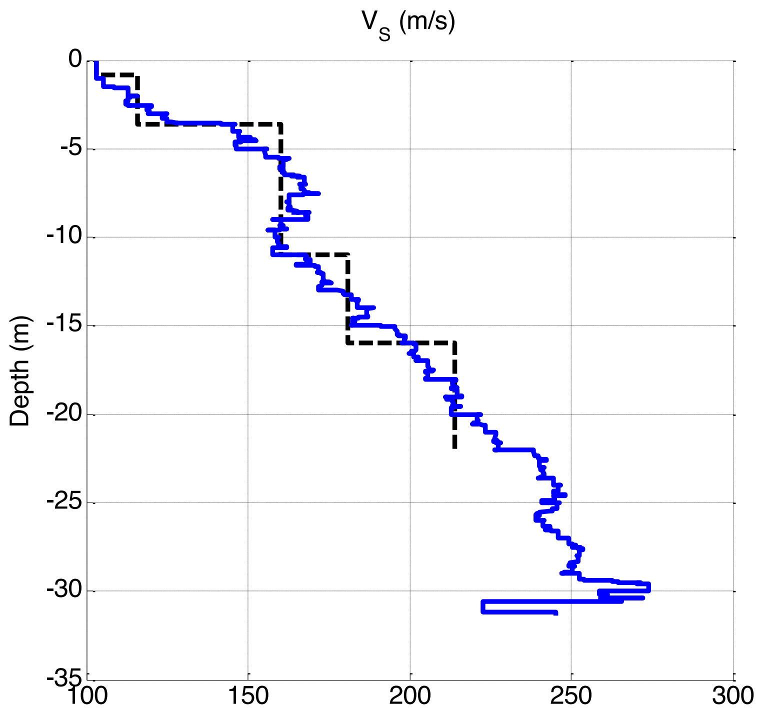


Figure 4.9: Definition of shear wave velocity profile for impedance function calculation: Mean reference profile with Scaling factor SF1 (blue lines); input profile for layered medium (black line).

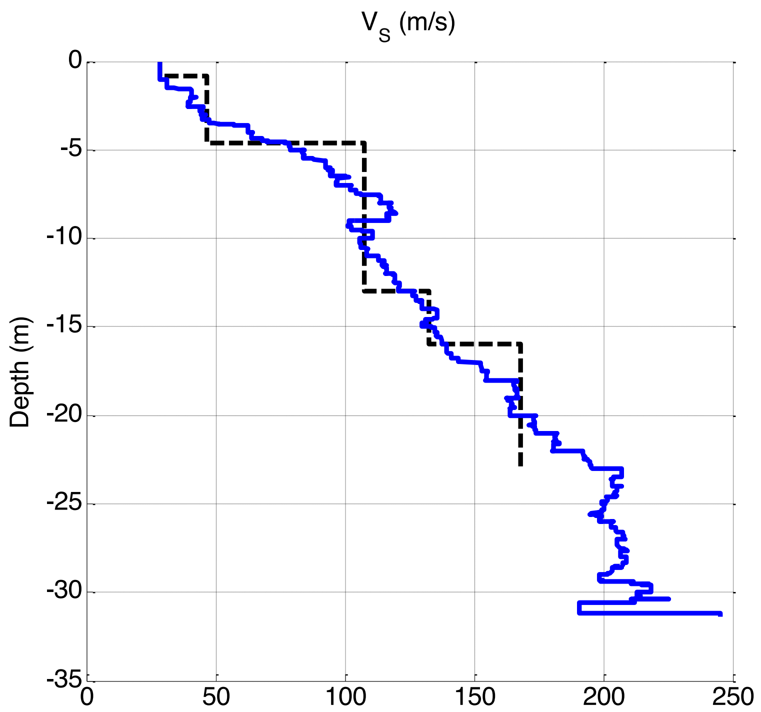


Figure 4.10: Definition of shear wave velocity profile for impedance function calculation: Mean – standard deviation reference profile with Scaling factor SF1 (blue lines); input profile for layered medium (black line).

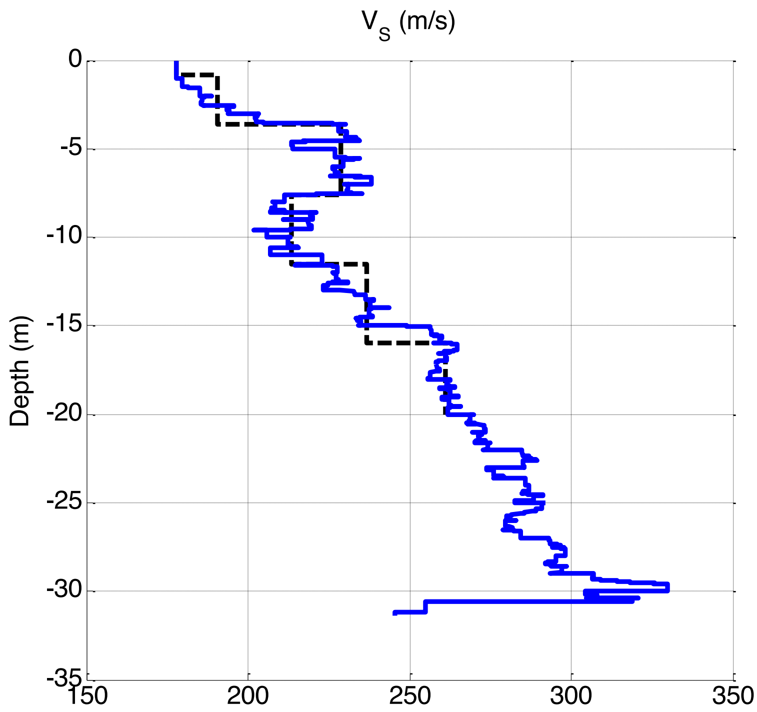


Figure 4.11: Definition of shear wave velocity profile for impedance function calculation: Mean + standard deviation reference profile with Scaling factor SF1 (blue lines); input profile for layered medium (black line).

5 Impedance functions for buildings on shallow foundations

The soil model selected for buildings on shallow foundations is the composite medium constituted by a layer on half-space. The layer is characterized by non-uniform shear wave velocity (i.e. linear increase). For composite medium the input parameters for definition of soil profile are: layer height (h); layer shear wave velocity; layer soil unit weight; layer Poisson's ratio; layer-half space shear wave velocity ratio. For embedded foundations, the code allows the user to input the properties of the soil adjacent to foundation considering the following parameters: thickness; shear wave velocity; unit weight; Poisson's ratio; damping ratio. The soil parameters used for shallow foundations are summarized in section 4.1.3.1.

The foundations of the buildings are constituted by a grid of orthogonal foundation beams, the foundation characteristics required by the code include: the equivalent lengths in the x and y directions (L_x,L_y) of the foundation, the coordinates of the foundation centre of gravity (X_c,Y_c,Z_c), the mass moments of inertia (I_{xx},I_{yy},I_{zz},I_{xy},I_{xz},I_{yz}) of the foundation. Because the foundation is not rectangular, the representative length (L_x and L_y) are calculated so that the area of the equivalent rectangular footing is equal to the contact area of the actual footing.

Impedance functions will be calculated considering the following cases:

- 2 building typologies: Detached and Terraced with 2,4,6 and 8 units;
- 2 foundations materials (concrete and masonry);
- 3 reference shear wave velocity profiles (mean; mean – st dev; mean + st dev);
- 3 shear wave velocity scaling factors accounting for different level of non linearity;

For a total number of 63 cases.

5.1 Detached building

Figure 5.1 shows the scheme of the foundations of the Detached building typology. The following sections show the impedance functions (in terms of frequency dependent stiffness and damping) of the building taking into account the three reference soil profiles defined in section 4.1.1 and the three scaling factors define in section 4.1.2. The foundations characteristics are summarized in the following tables.

Table 5.1: Foundations characteristics of Detached building – Masonry foundations

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m²]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m²]	I_{yy} [kg m²]	I_{zz} [kg m²]	I_{xy} [kg m²]	I_{xz} [kg m²]	I_{yz} [kg m²]
11	12	0.26	31.1	5.34	5.82	15.5e3	220.6e3	218.0e3	438.4e3	-78.4e3	0	0

Table 5.2: Foundation characteristics of Detached building – Concrete foundations

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m²]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m²]	I_{yy} [kg m²]	I_{zz} [kg m²]	I_{xy} [kg m²]	I_{xz} [kg m²]	I_{yz} [kg m²]
11	12	0.33	18.7	4.13	4.51	14.8e3	209.2e3	206.7e3	415.7e3	-74.4e3	0	0

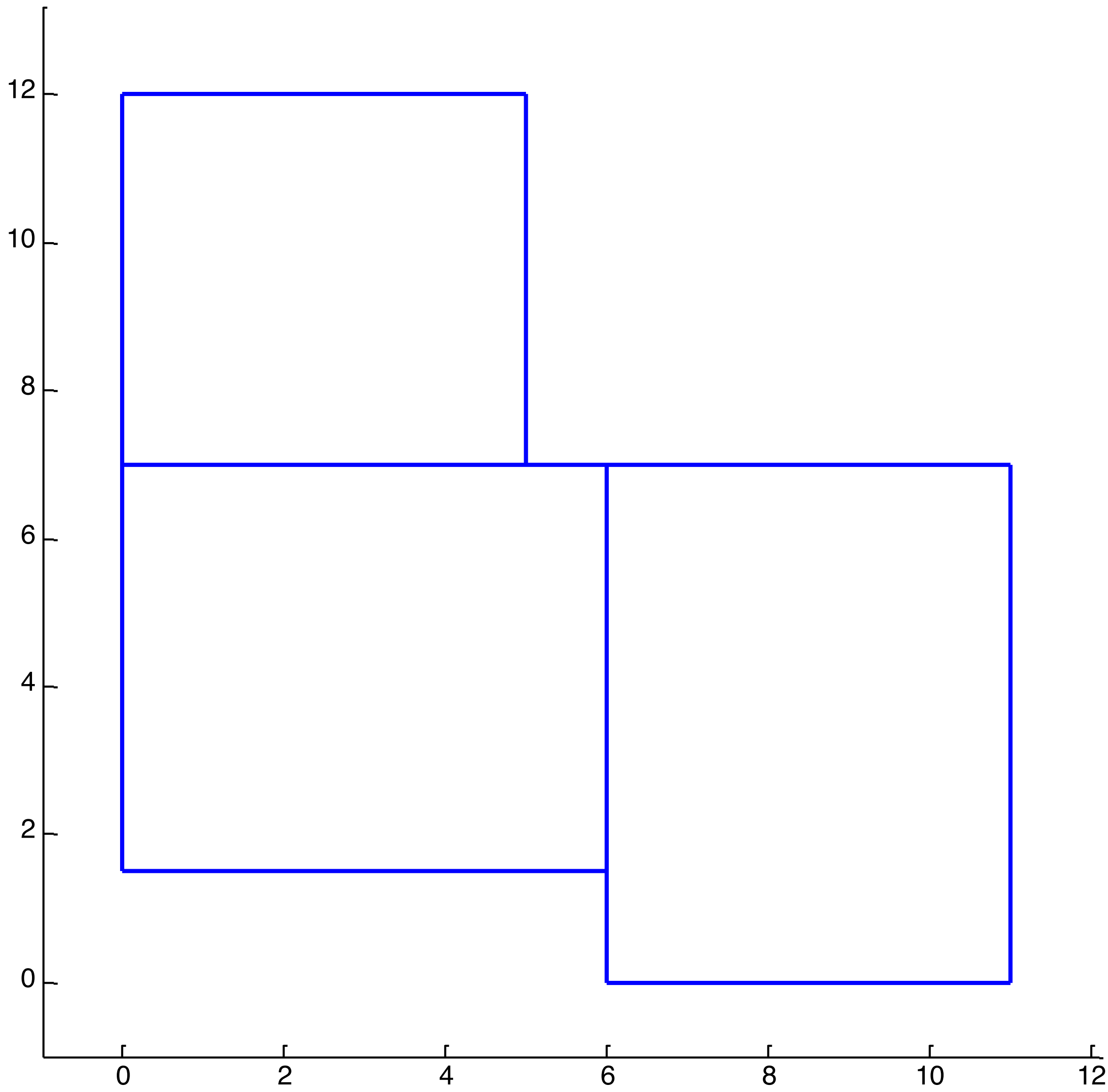


Figure 5.1: Detached building: schematic position of beam foundations

5.1.1 Masonry foundations

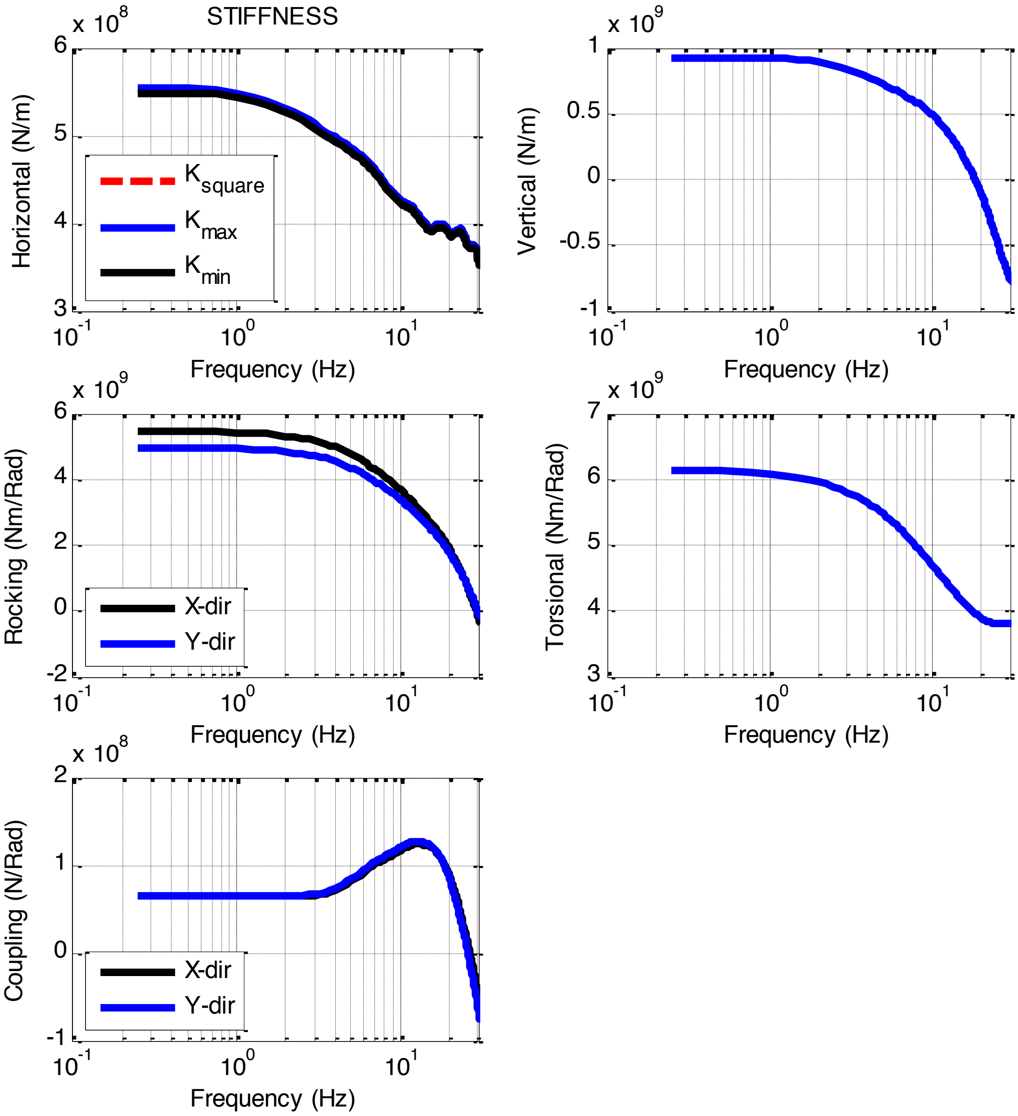


Figure 5.2: Detached Building on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF1: STIFFNESS

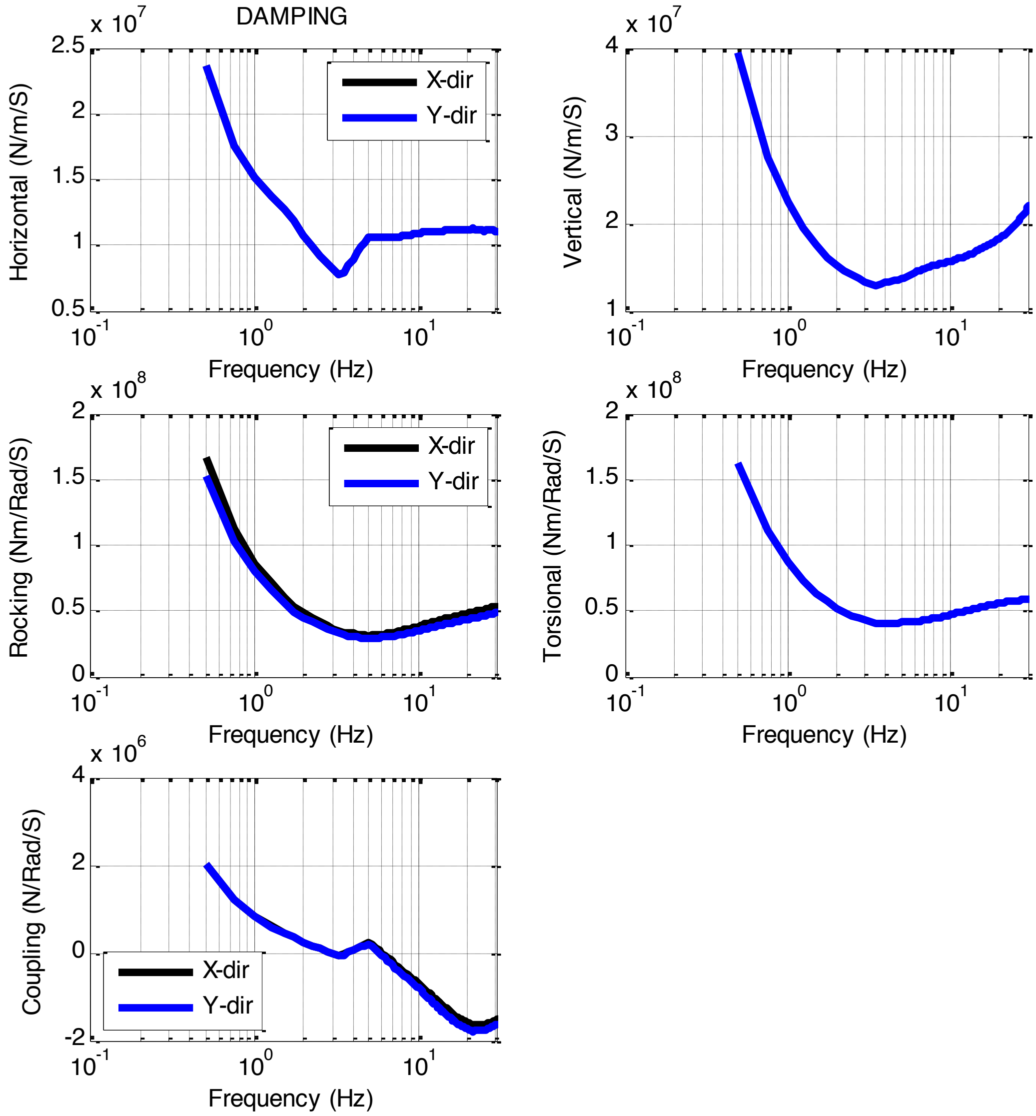


Figure 5.3: Detached Building on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF1: DAMPING

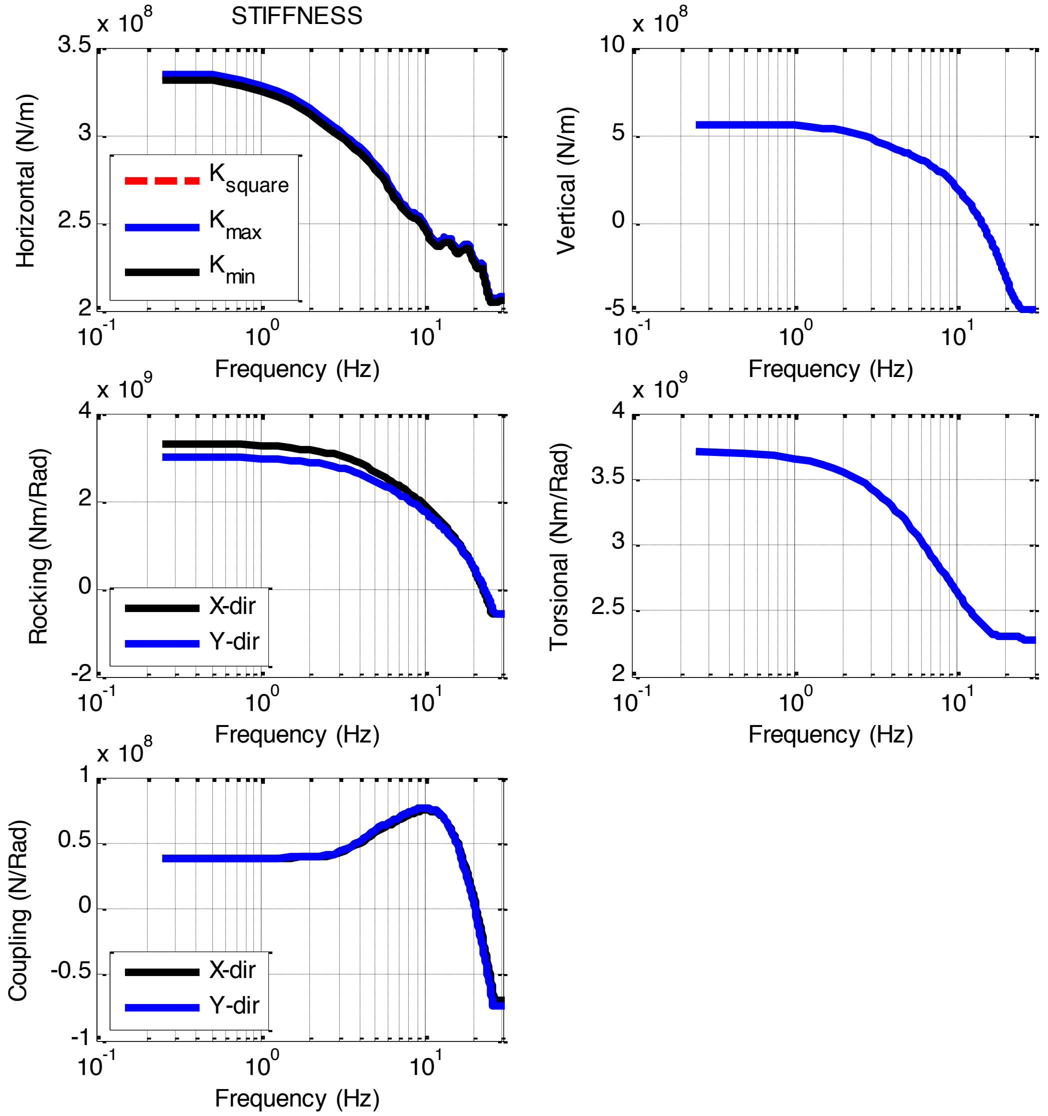


Figure 5.4: Detached Building on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF2: STIFFNESS

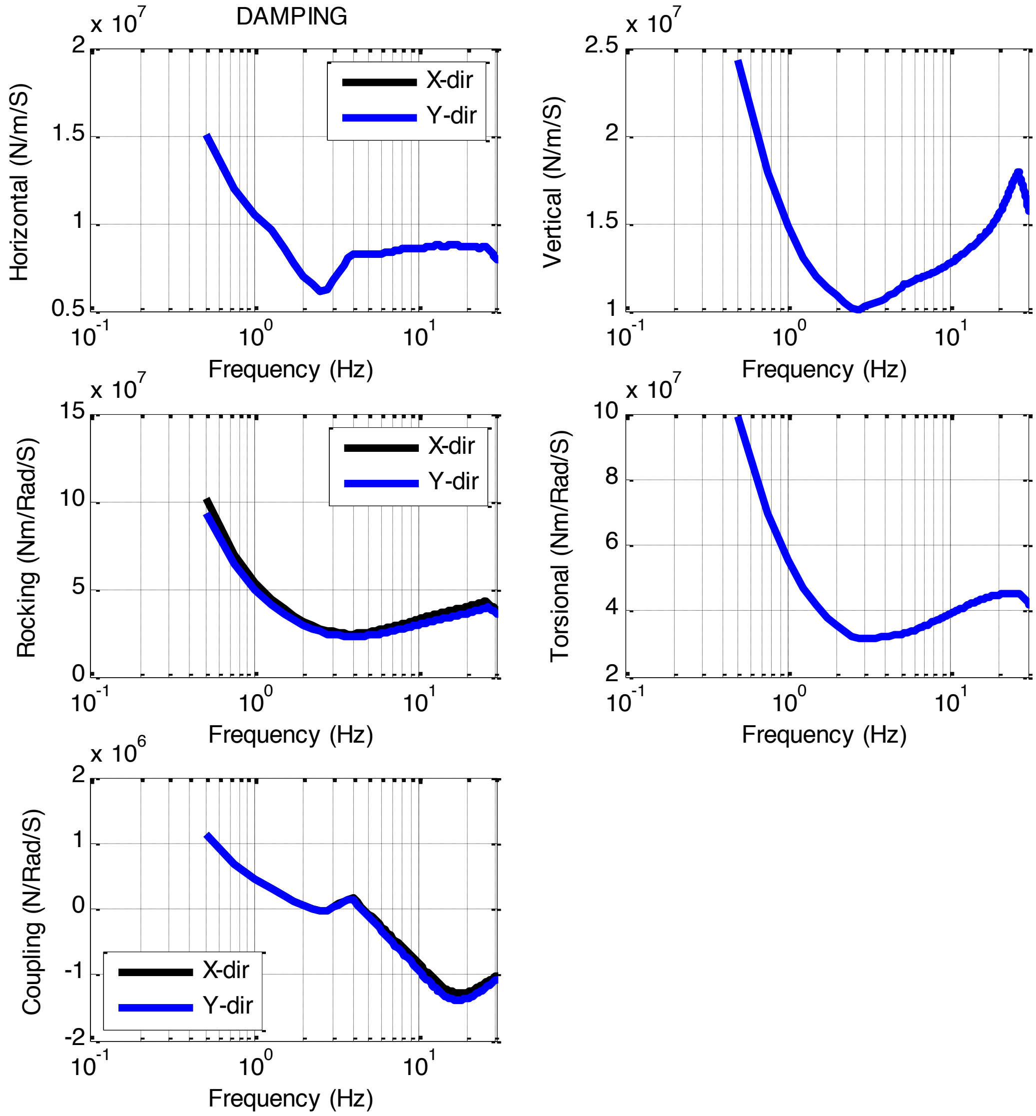


Figure 5.5: Detached Building on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF2: DAMPING

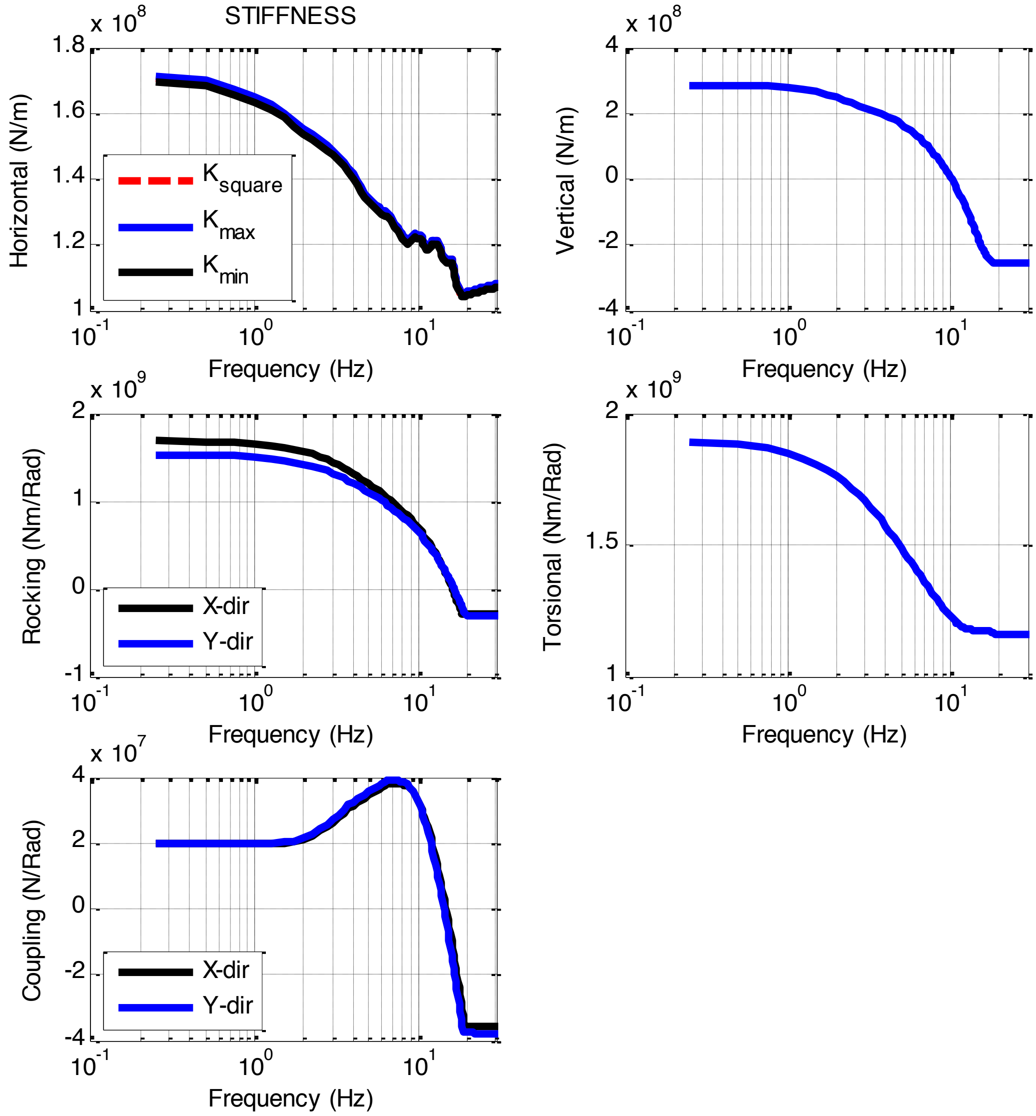


Figure 5.6: Detached Building on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF3: STIFFNESS

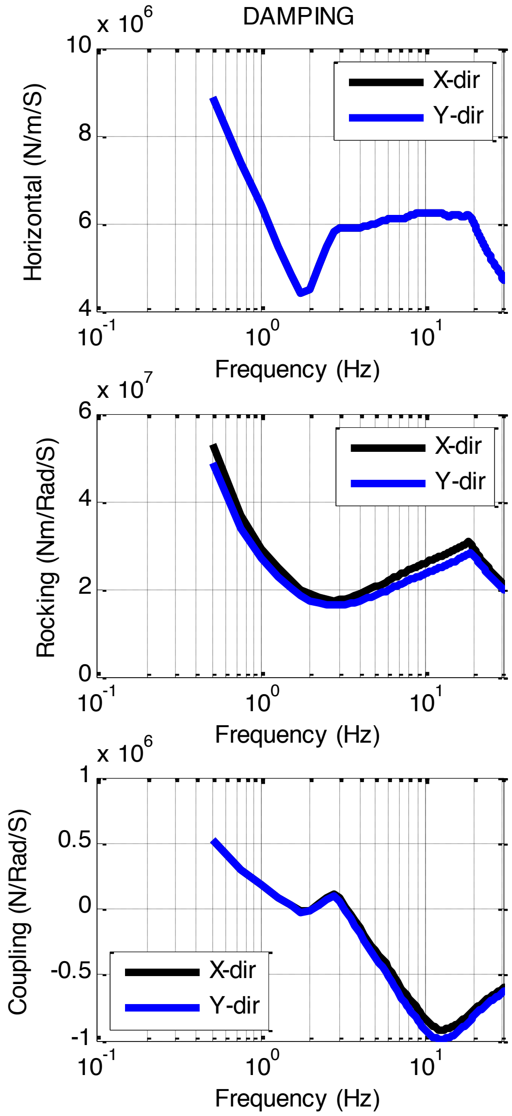


Figure 5.7: Detached Building on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF3: DAMPING

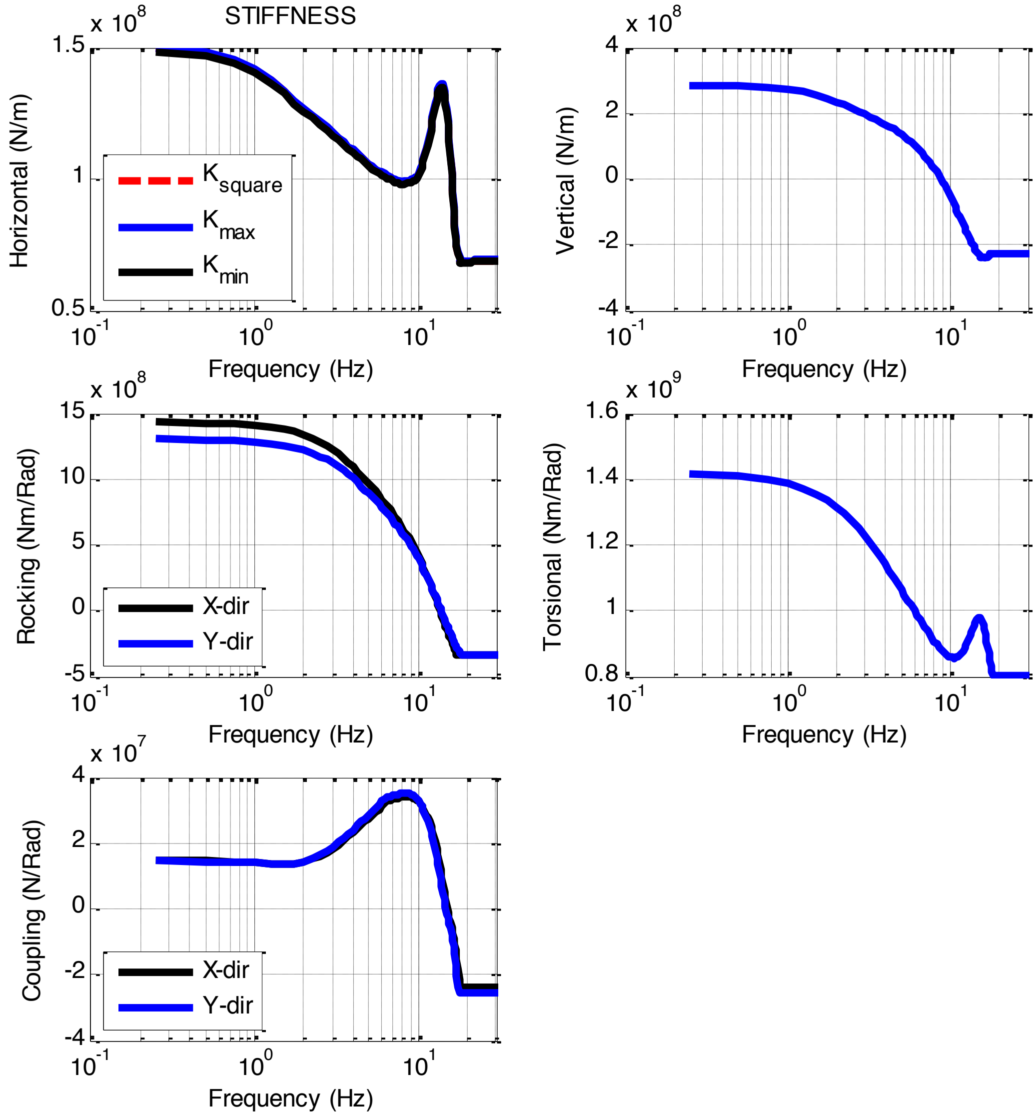


Figure 5.8: Detached Building on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

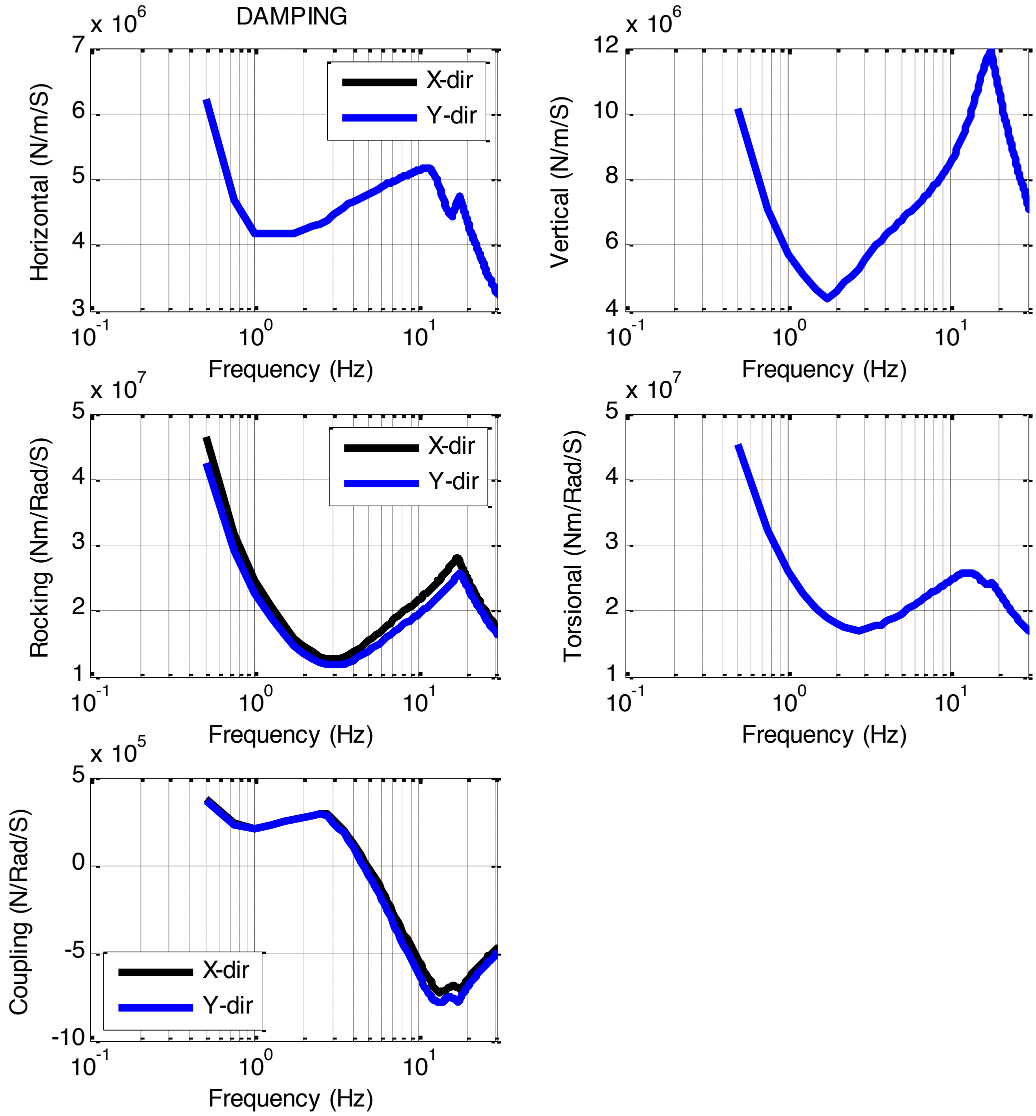


Figure 5.9: Detached Building on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

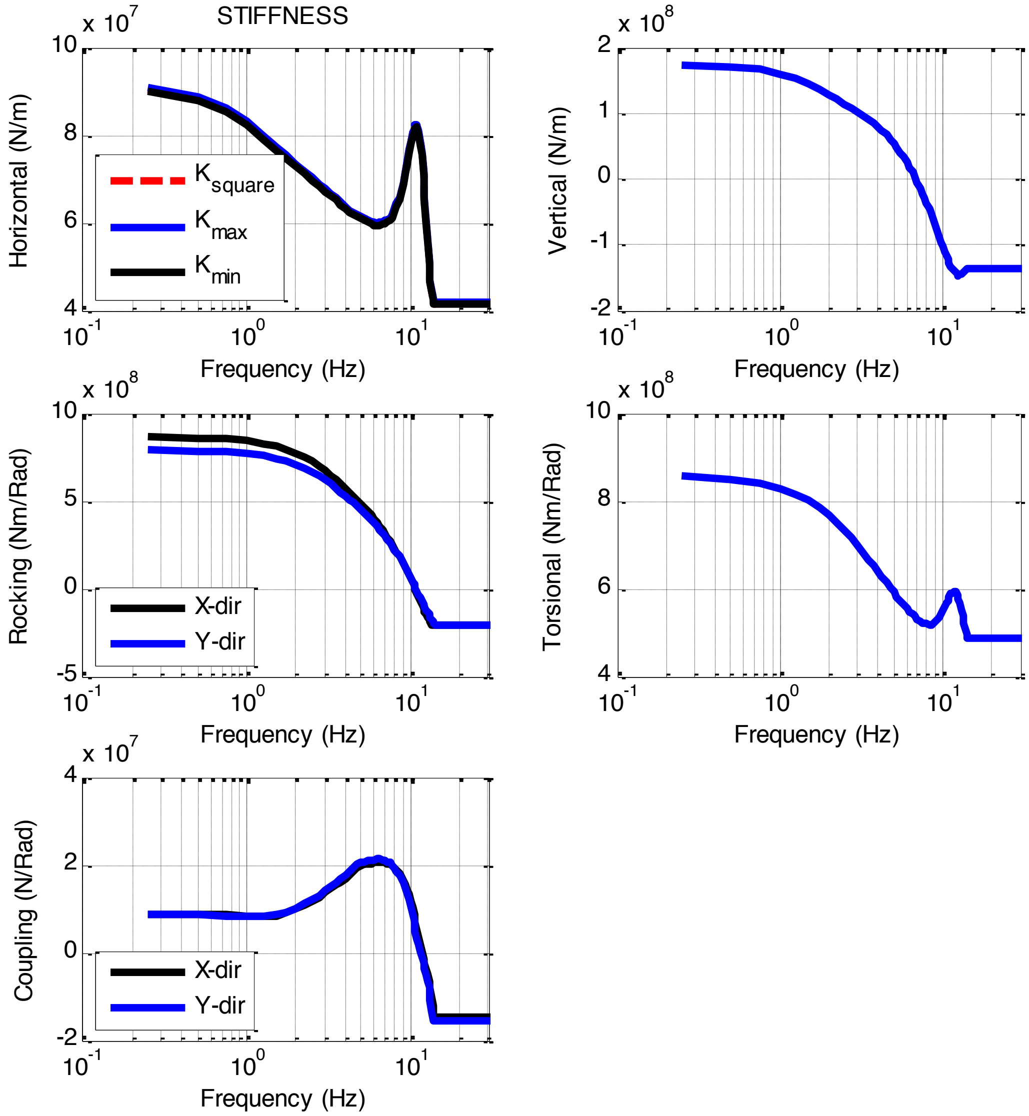


Figure 5.10: Detached Building on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

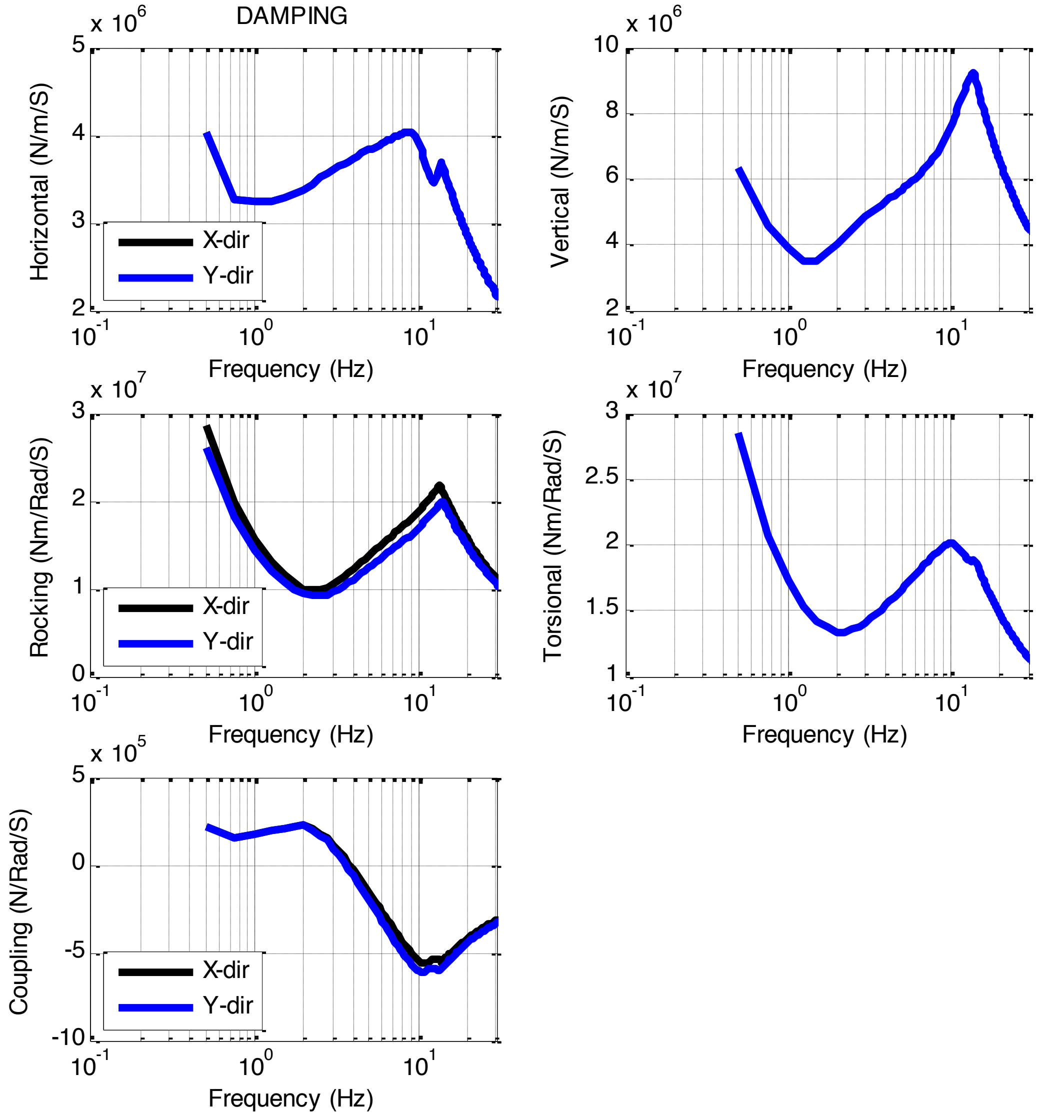


Figure 5.11: Detached Building on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

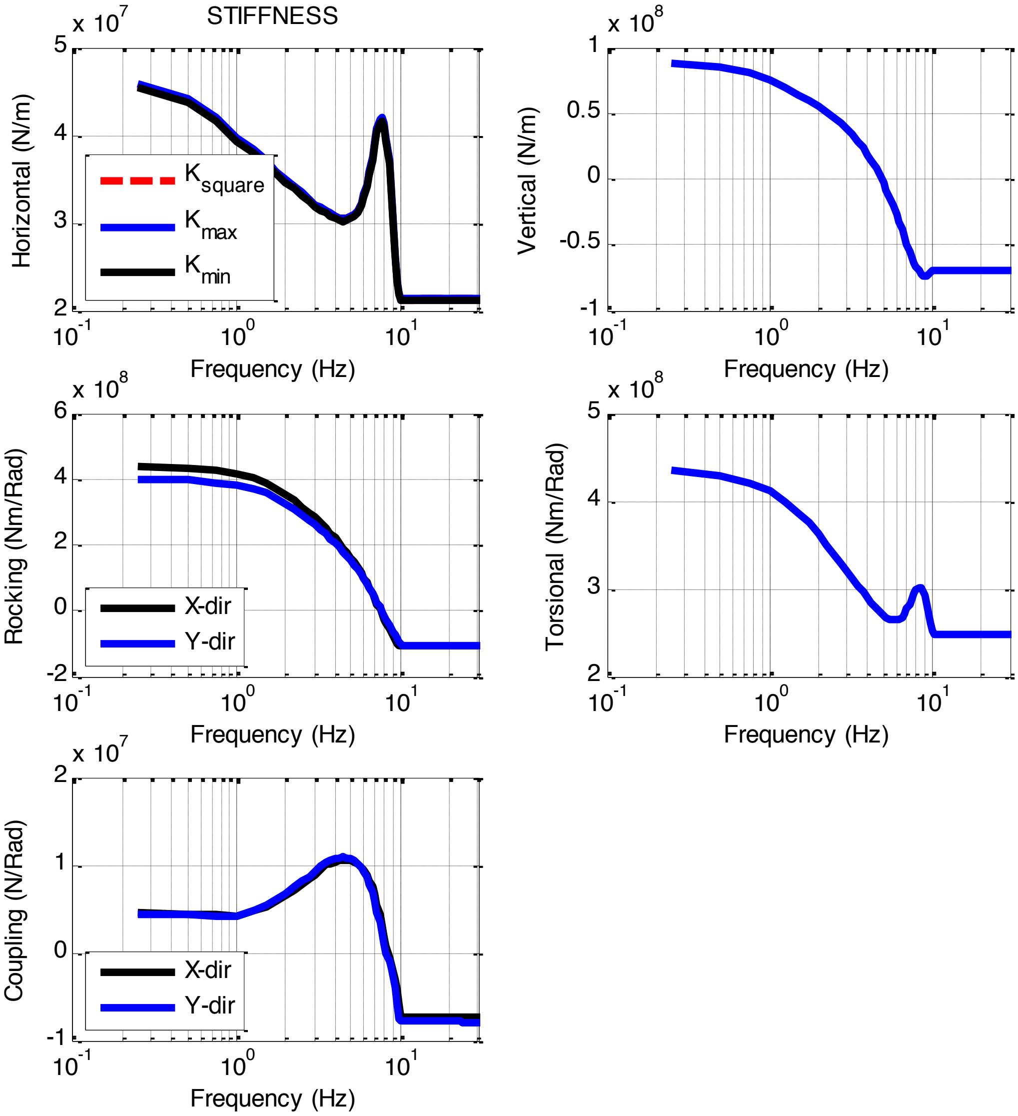


Figure 5.12: Detached Building on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

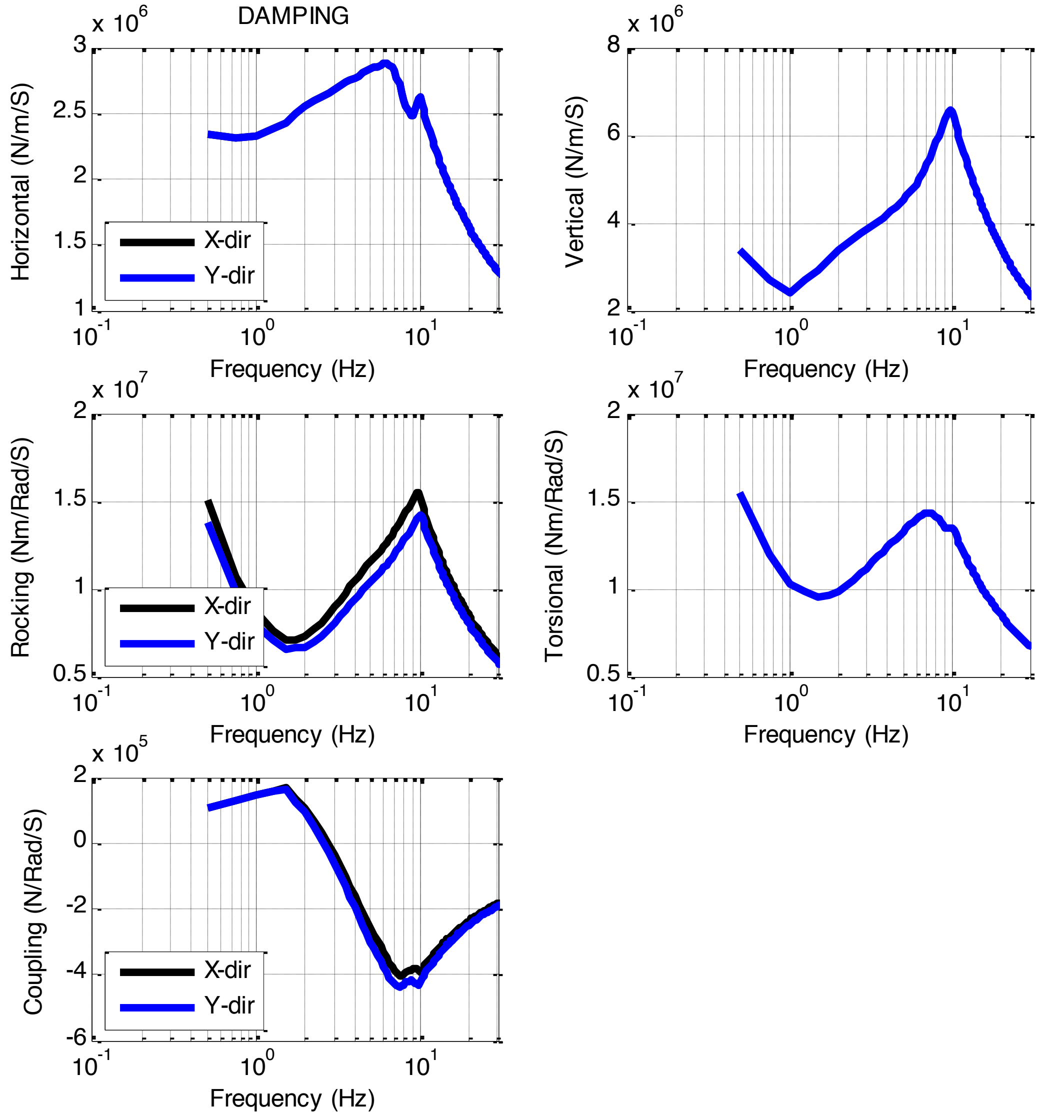


Figure 5.13: Detached Building on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

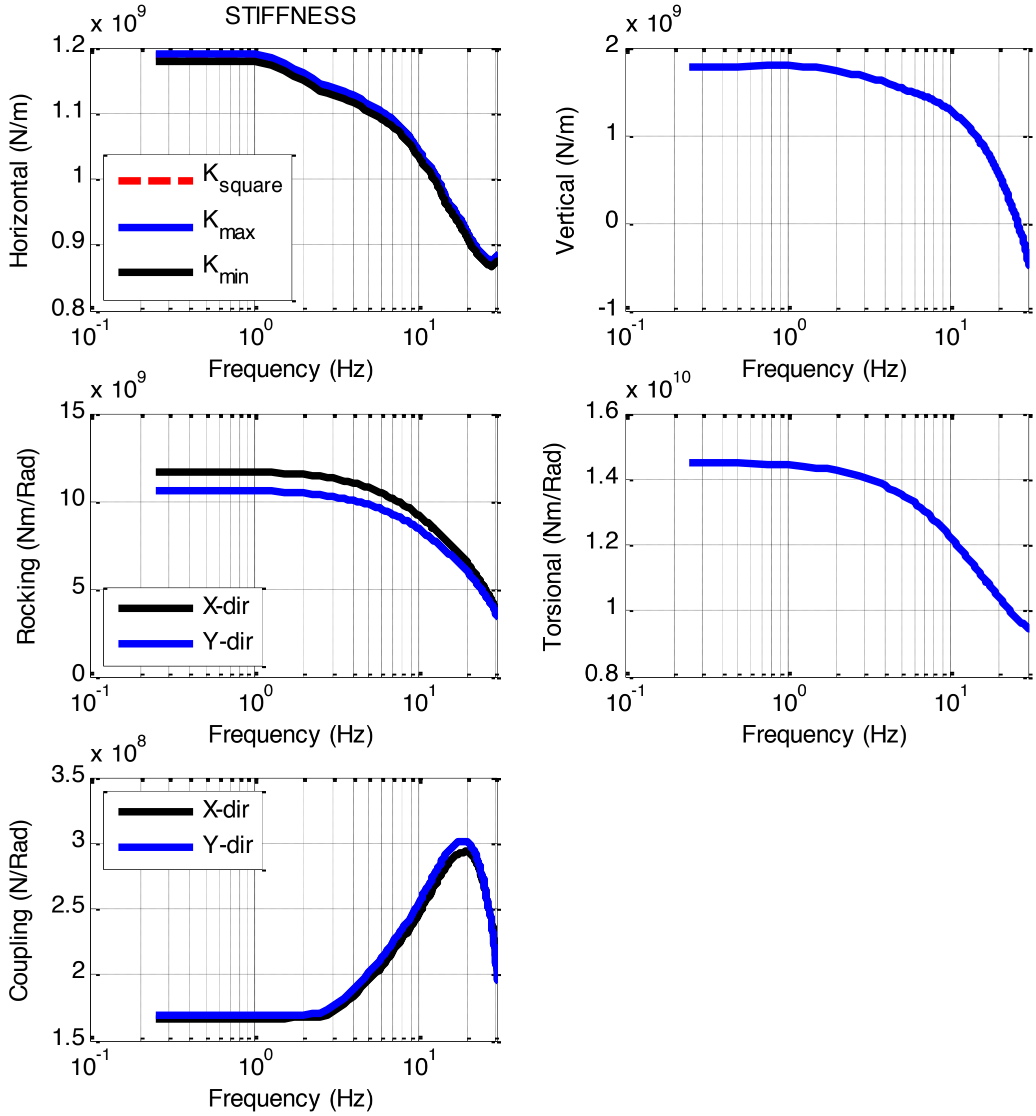


Figure 5.14: Detached Building on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

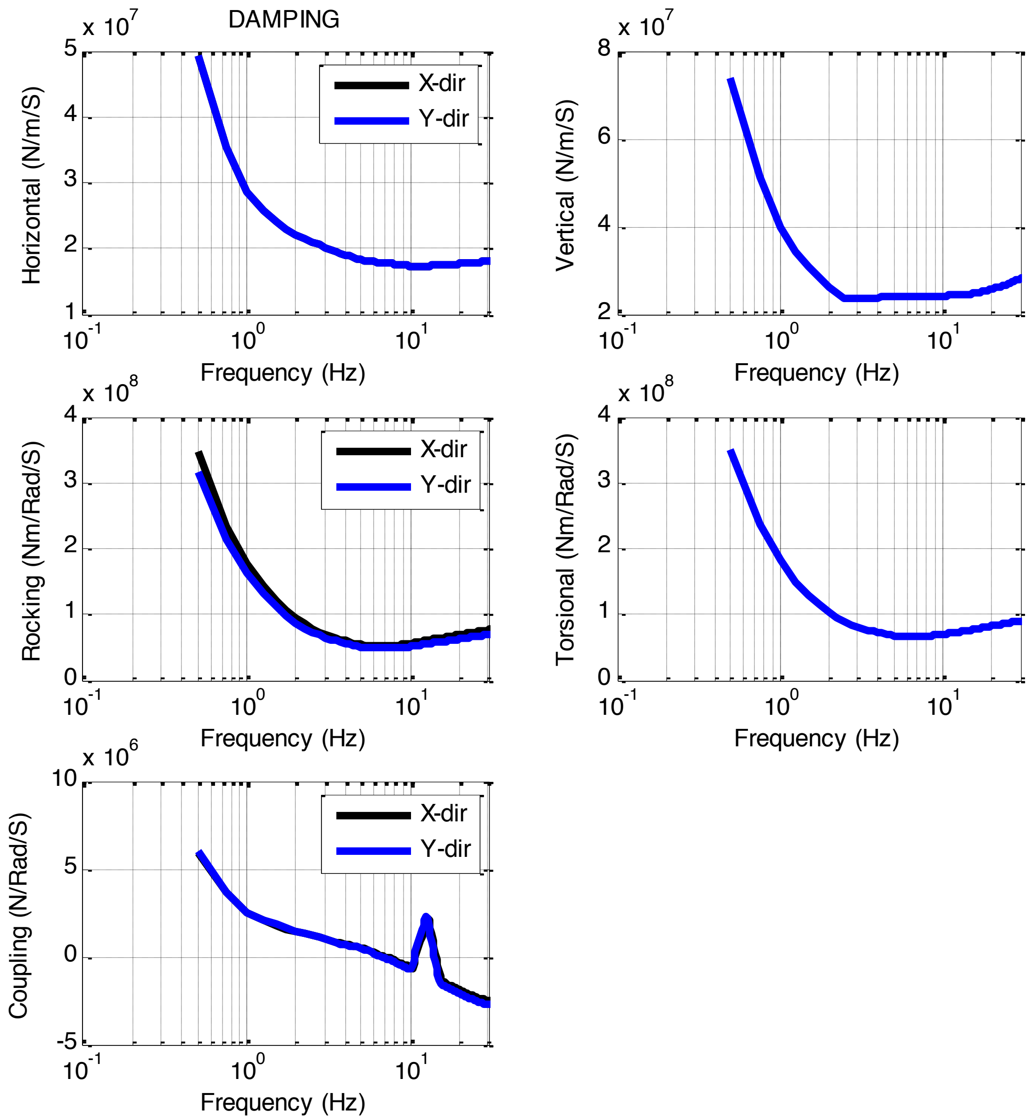


Figure 5.15: Detached Building on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

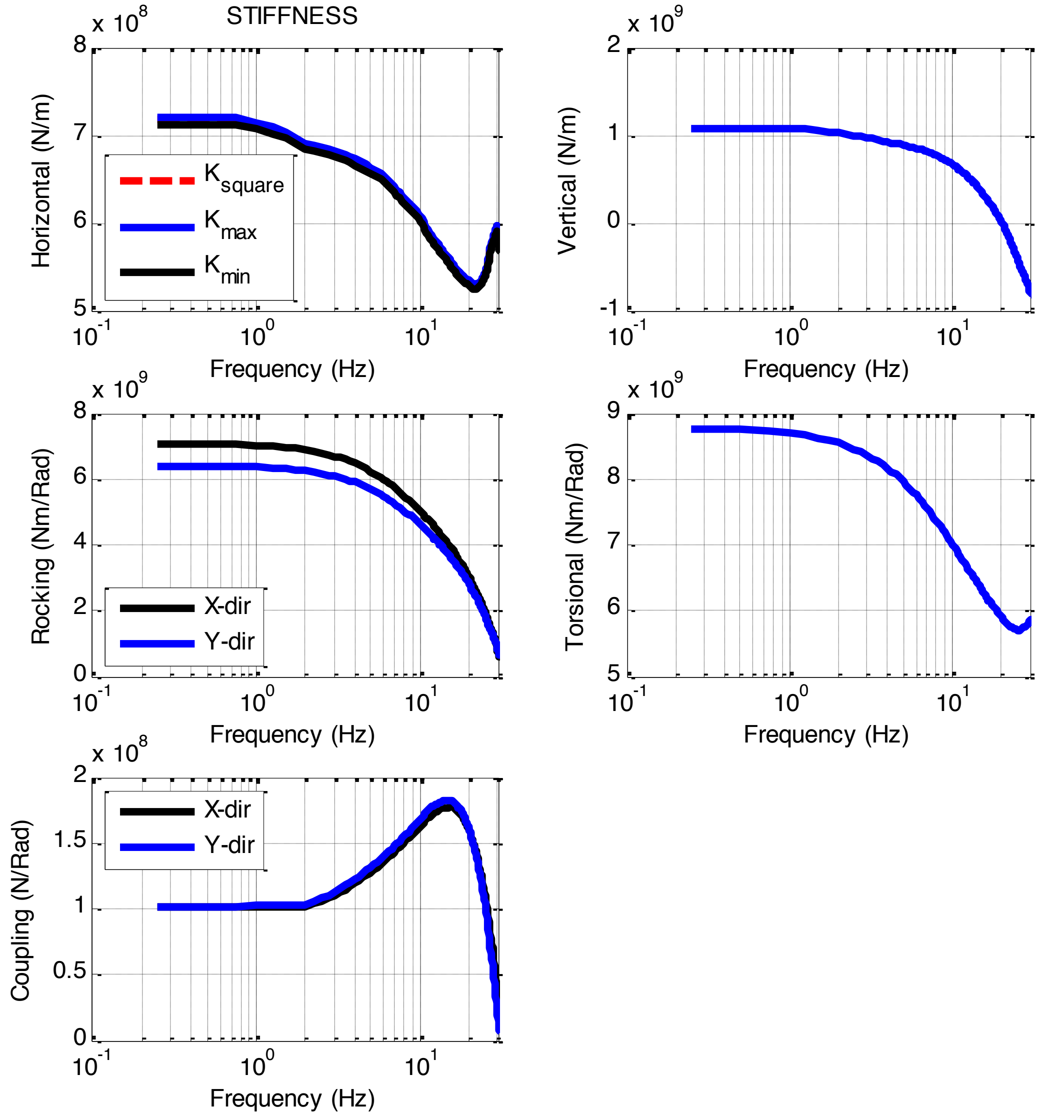


Figure 5.16: Detached Building on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

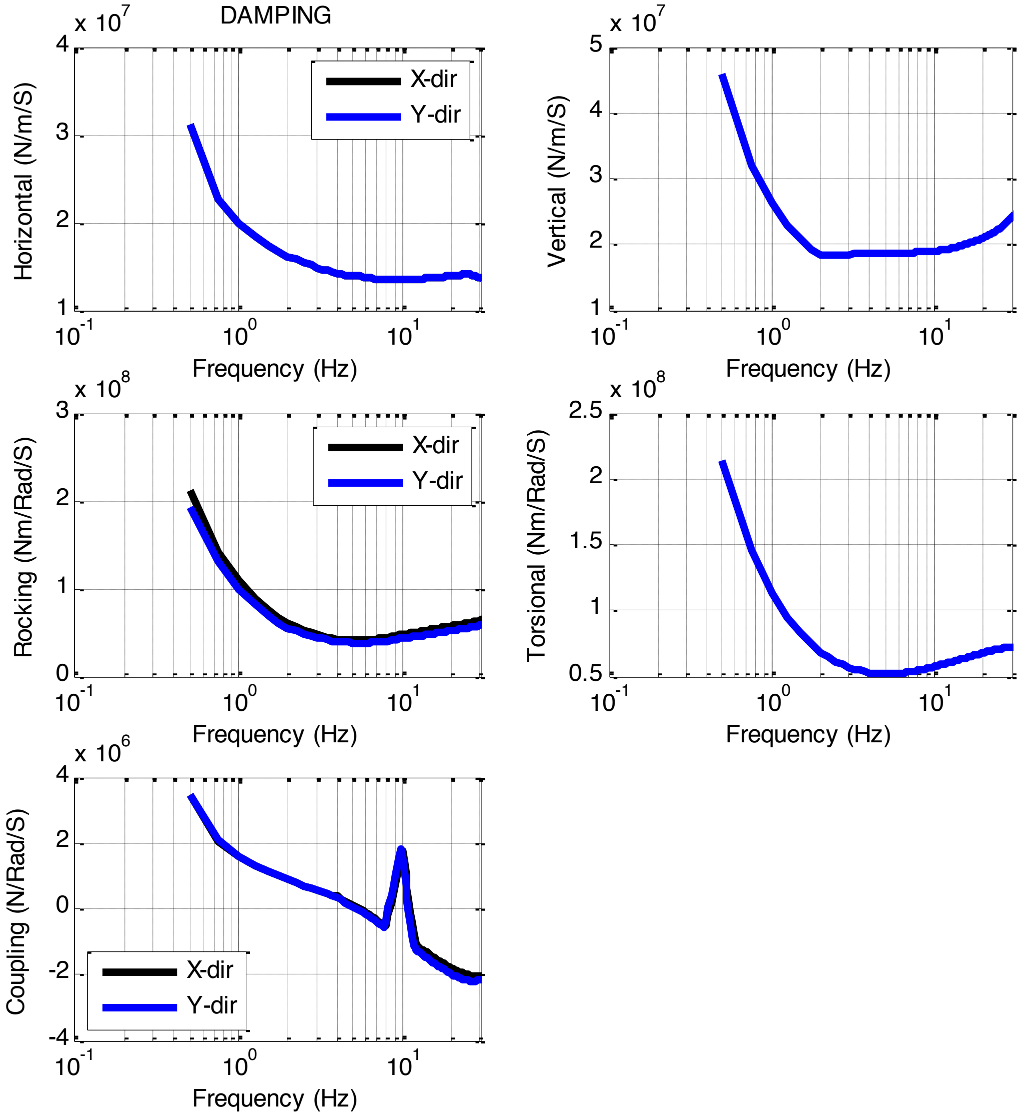


Figure 5.17: Detached Building on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

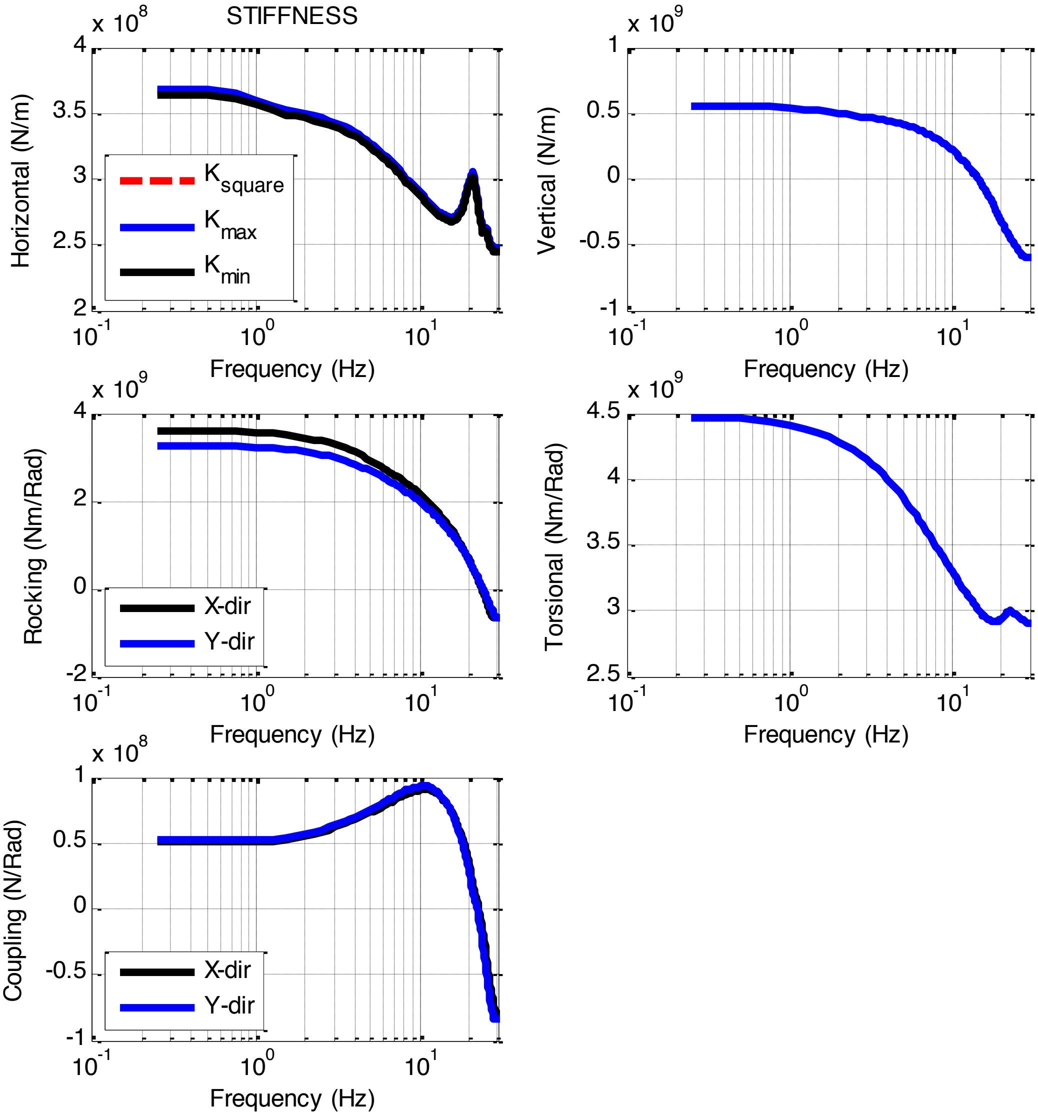


Figure 5.18: Detached Building on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

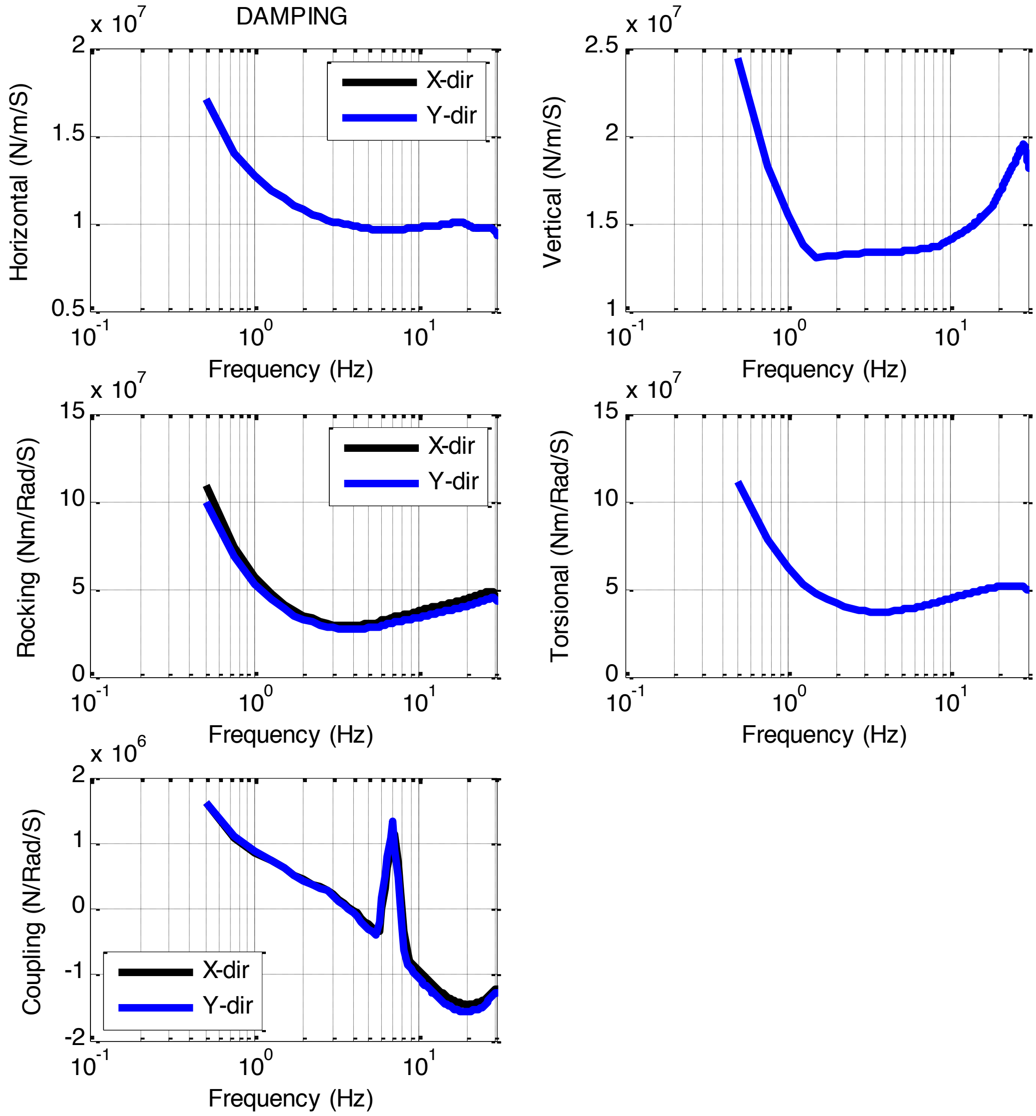


Figure 5.19: Detached Building on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

5.1.2 Concrete foundations

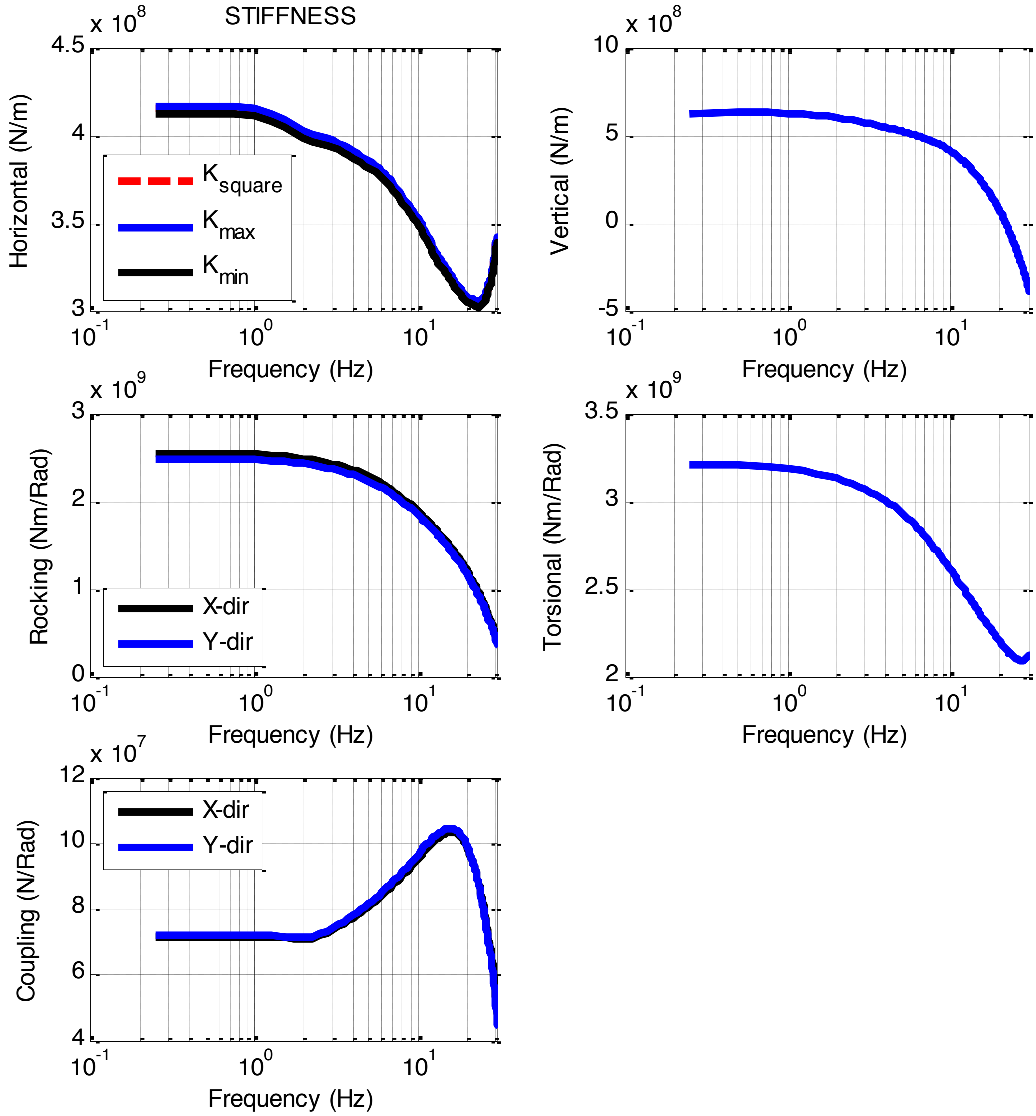


Figure 5.20: Detached Building on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: STIFFNESS

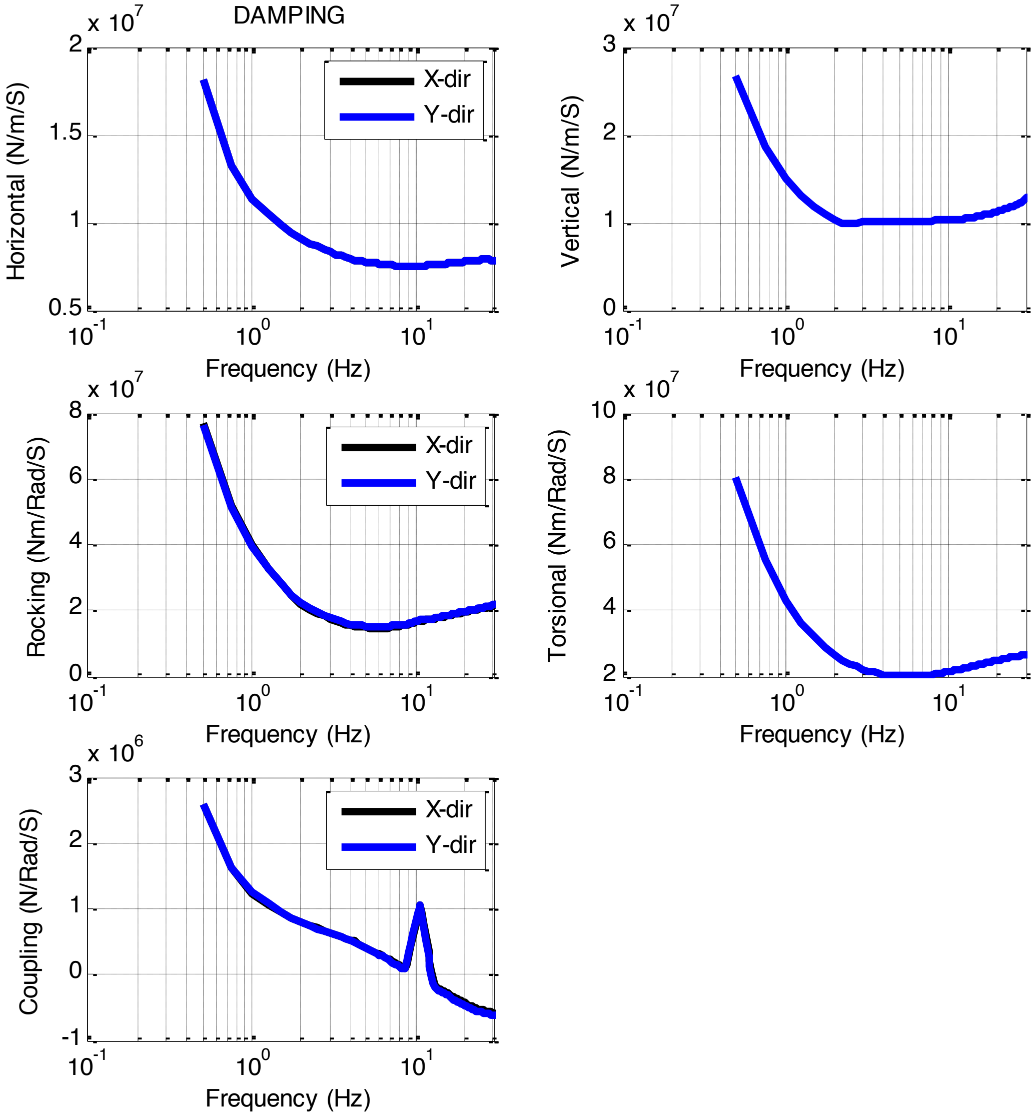


Figure 5.21: Detached Building on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: DAMPING

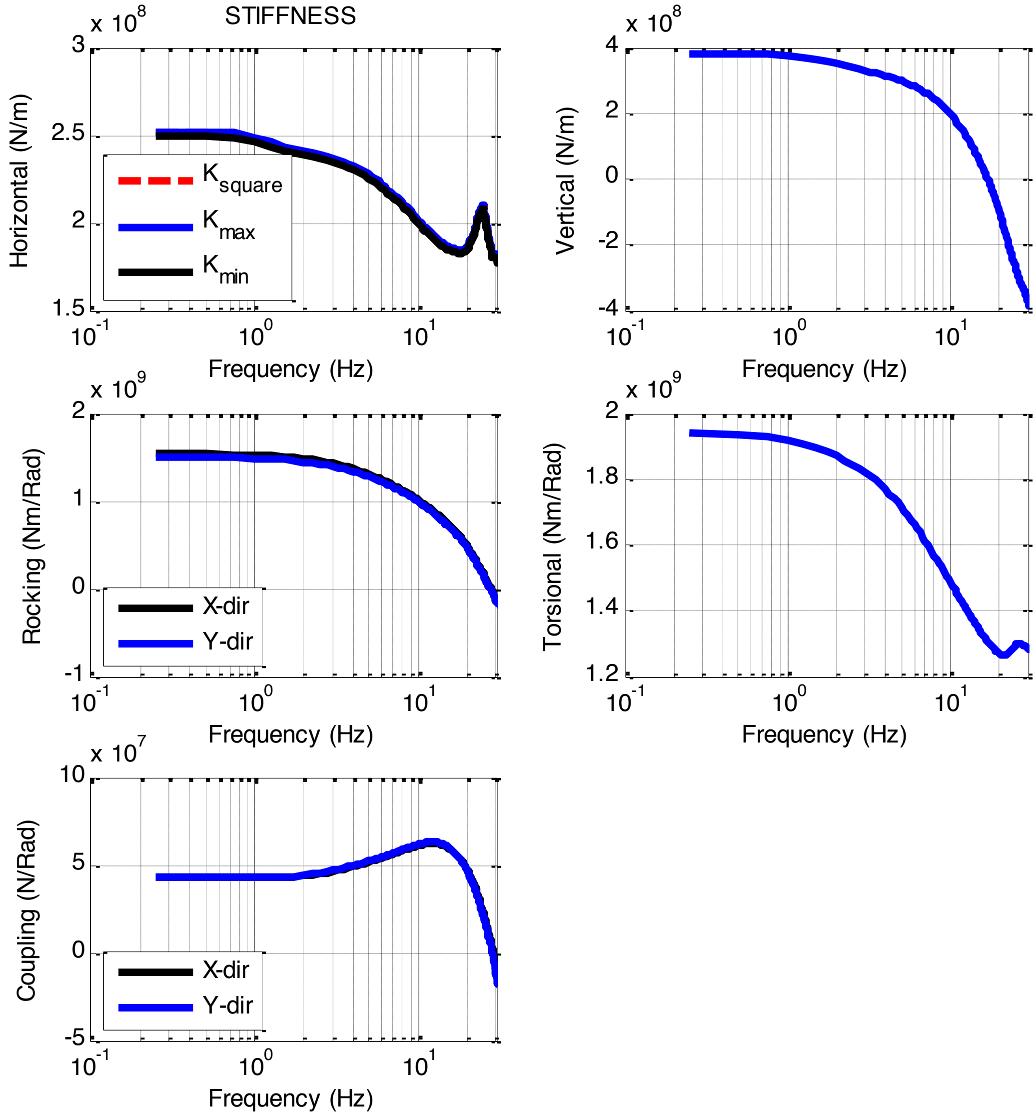


Figure 5.22: Detached Building on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: STIFFNESS

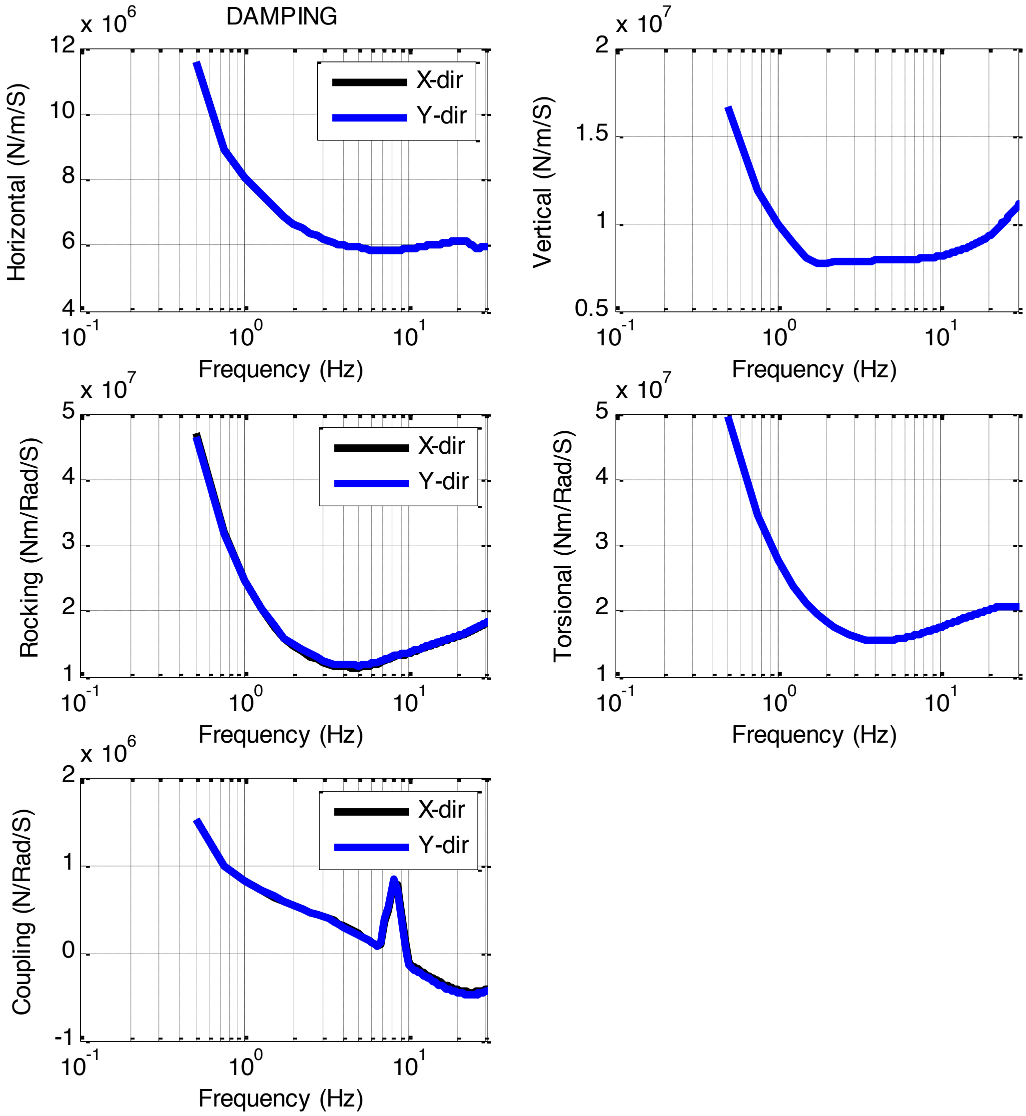


Figure 5.23: Detached Building on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: DAMPING

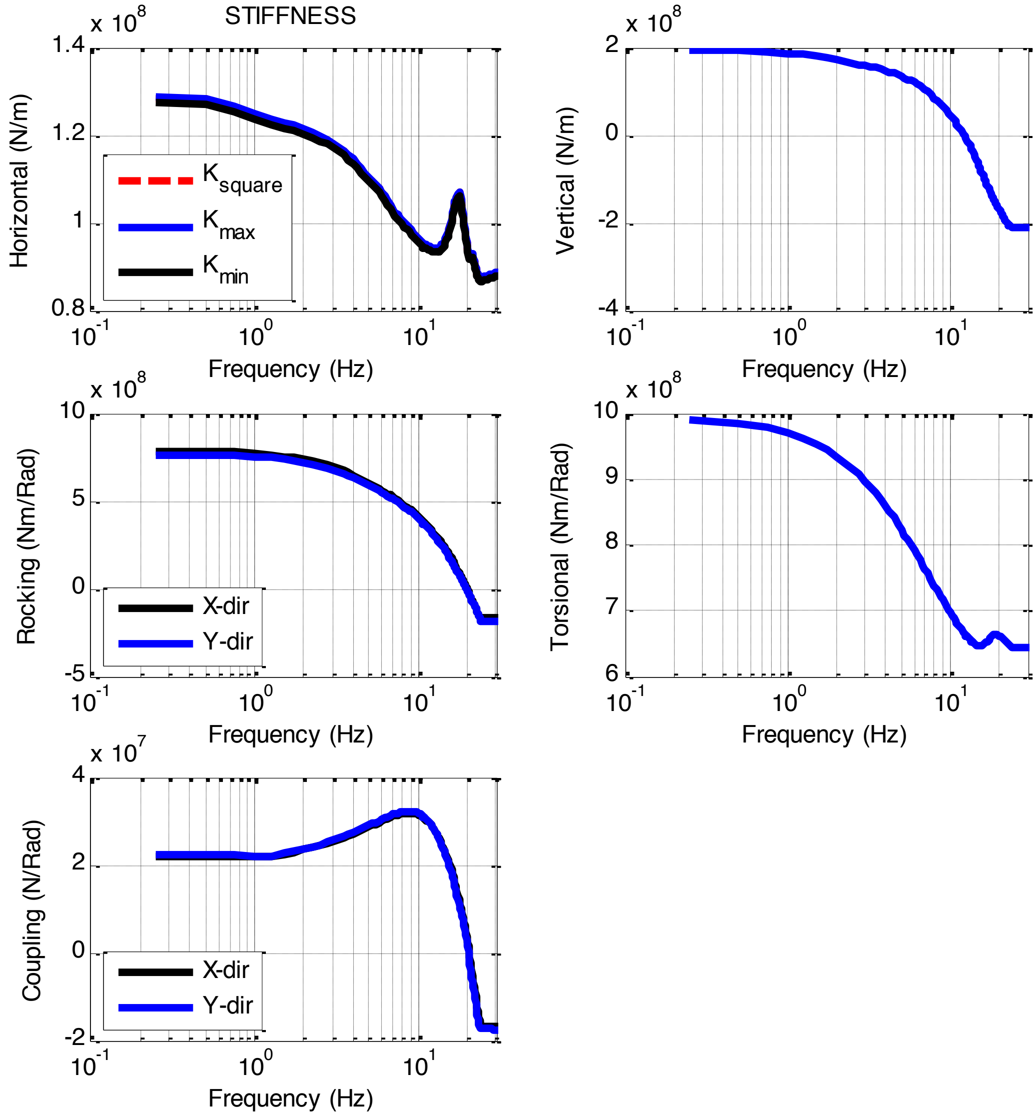


Figure 5.24: Detached Building on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: STIFFNESS

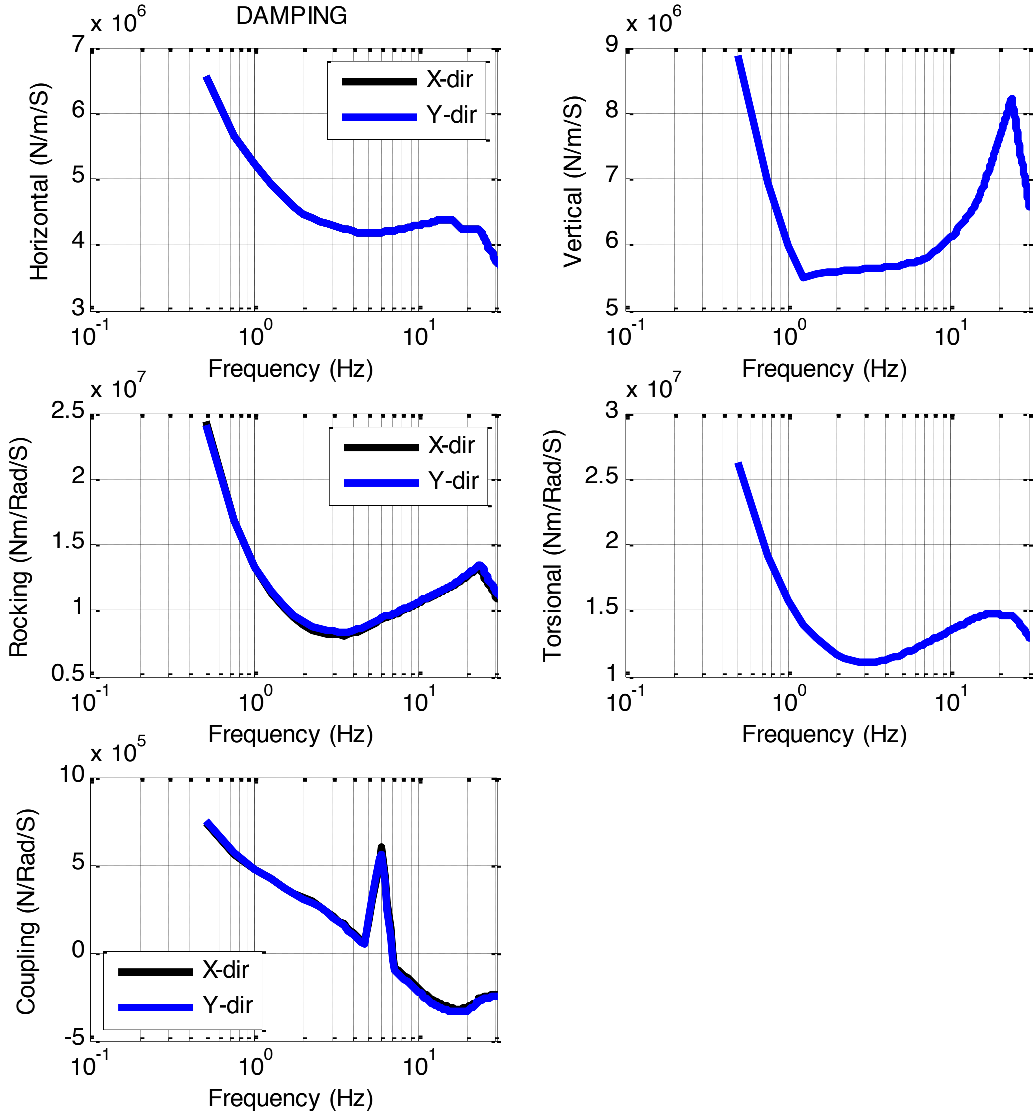


Figure 5.25: Detached Building on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: DAMPING

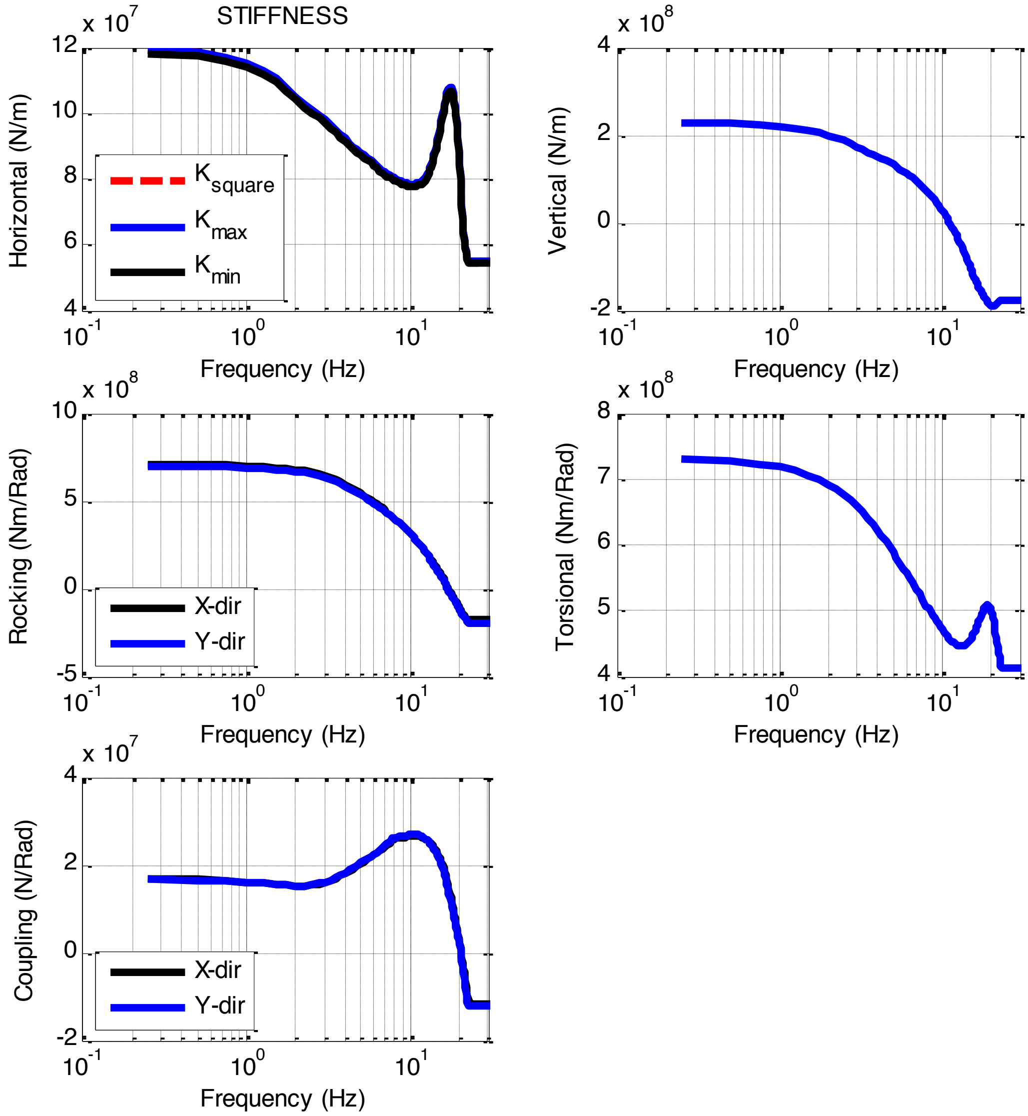


Figure 5.26: Detached Building on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

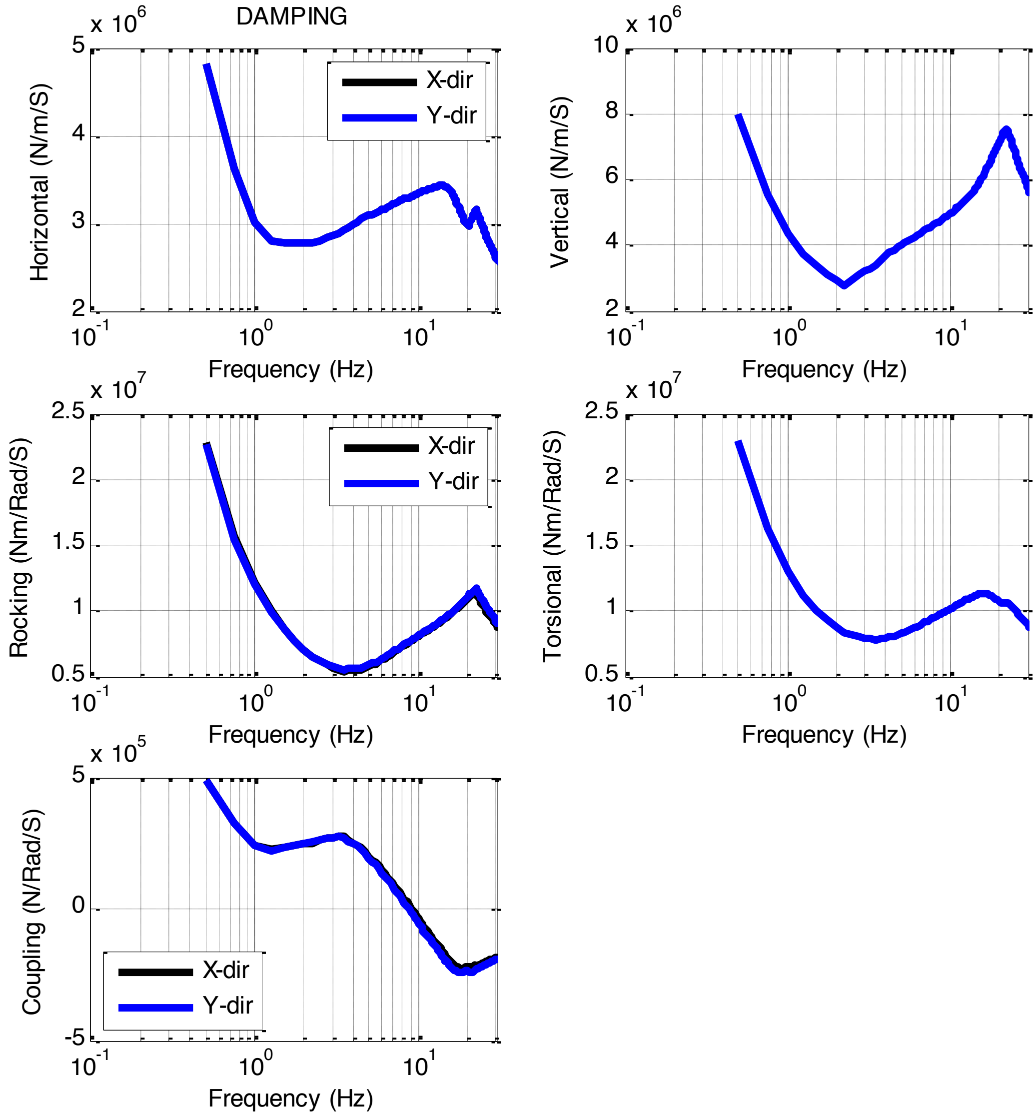


Figure 5.27: Detached Building on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

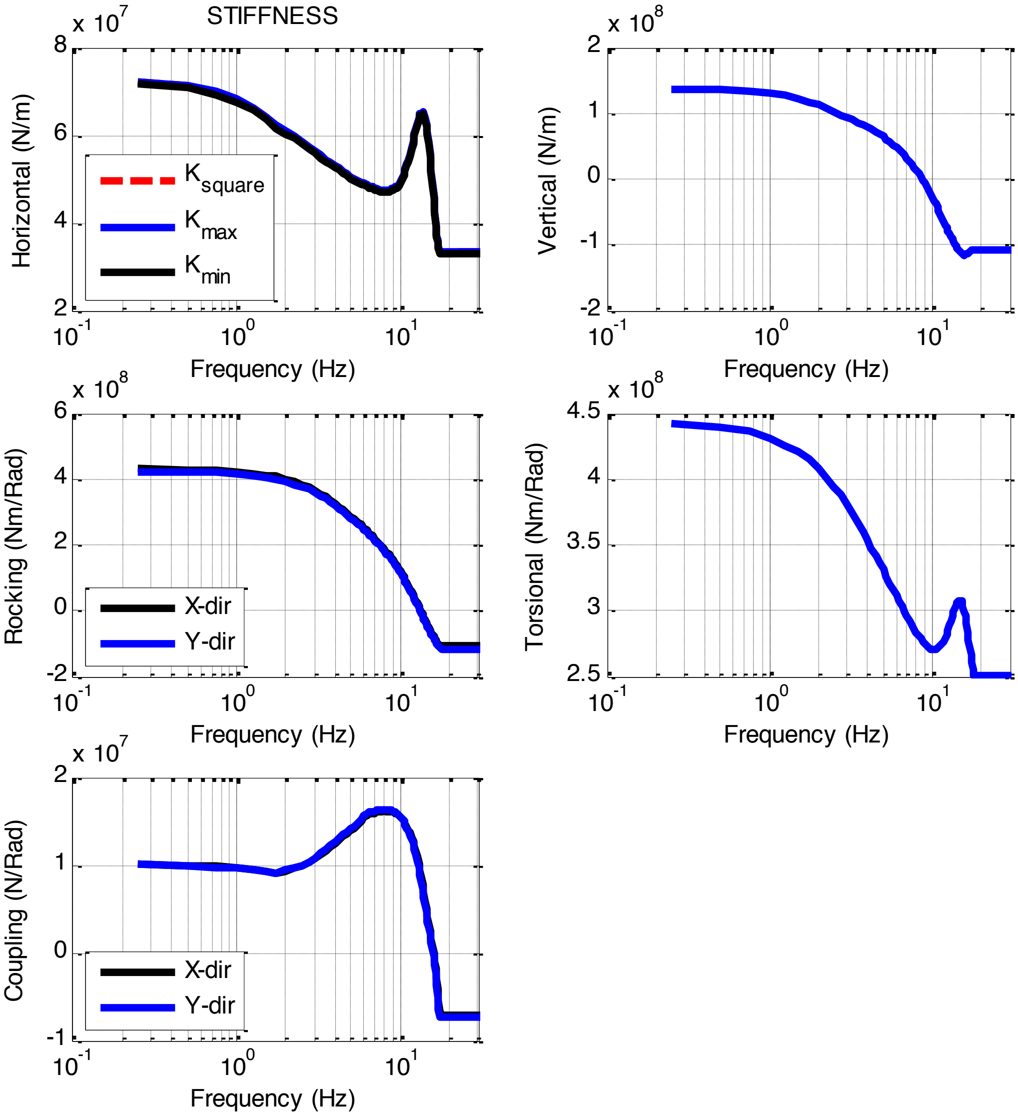


Figure 5.28: Detached Building on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

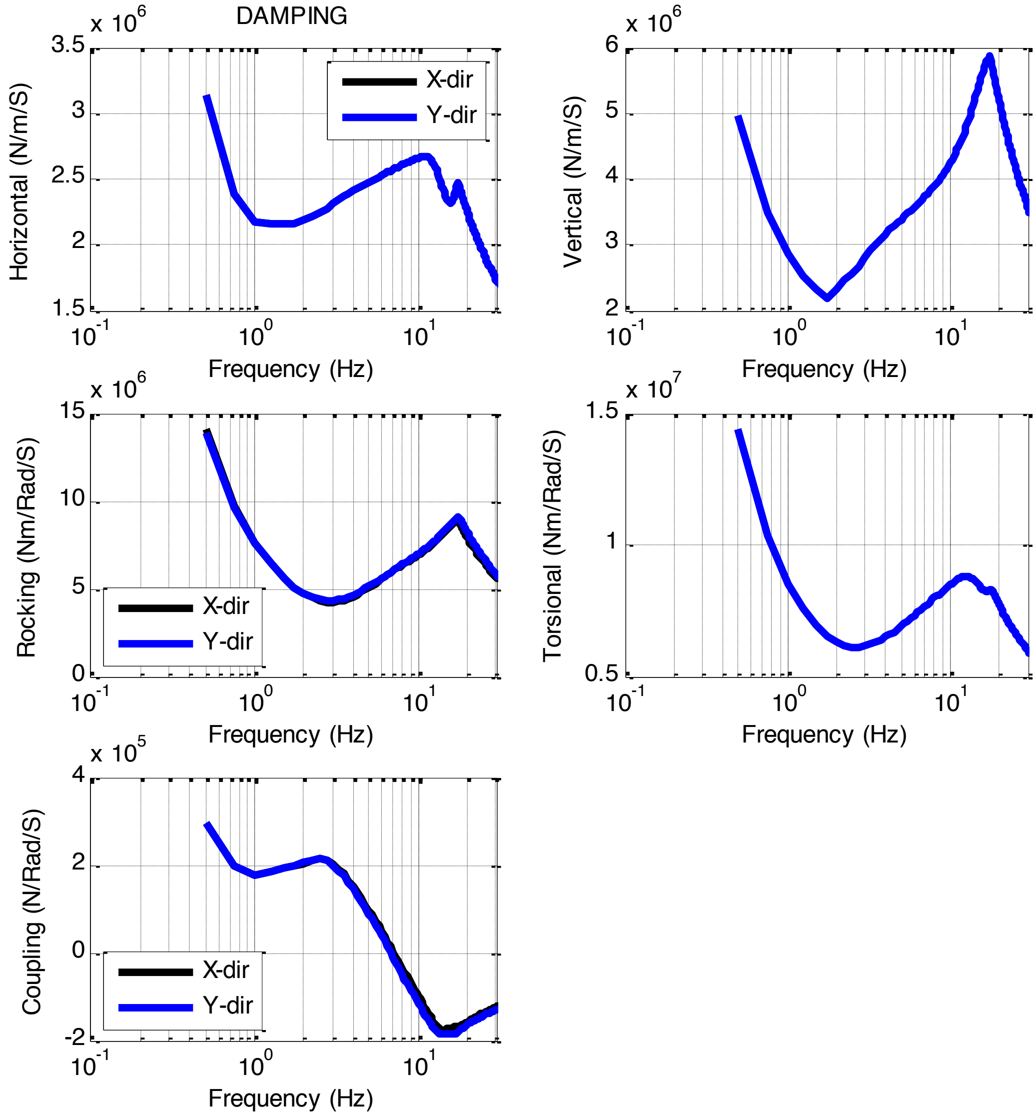


Figure 5.29: Detached Building on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

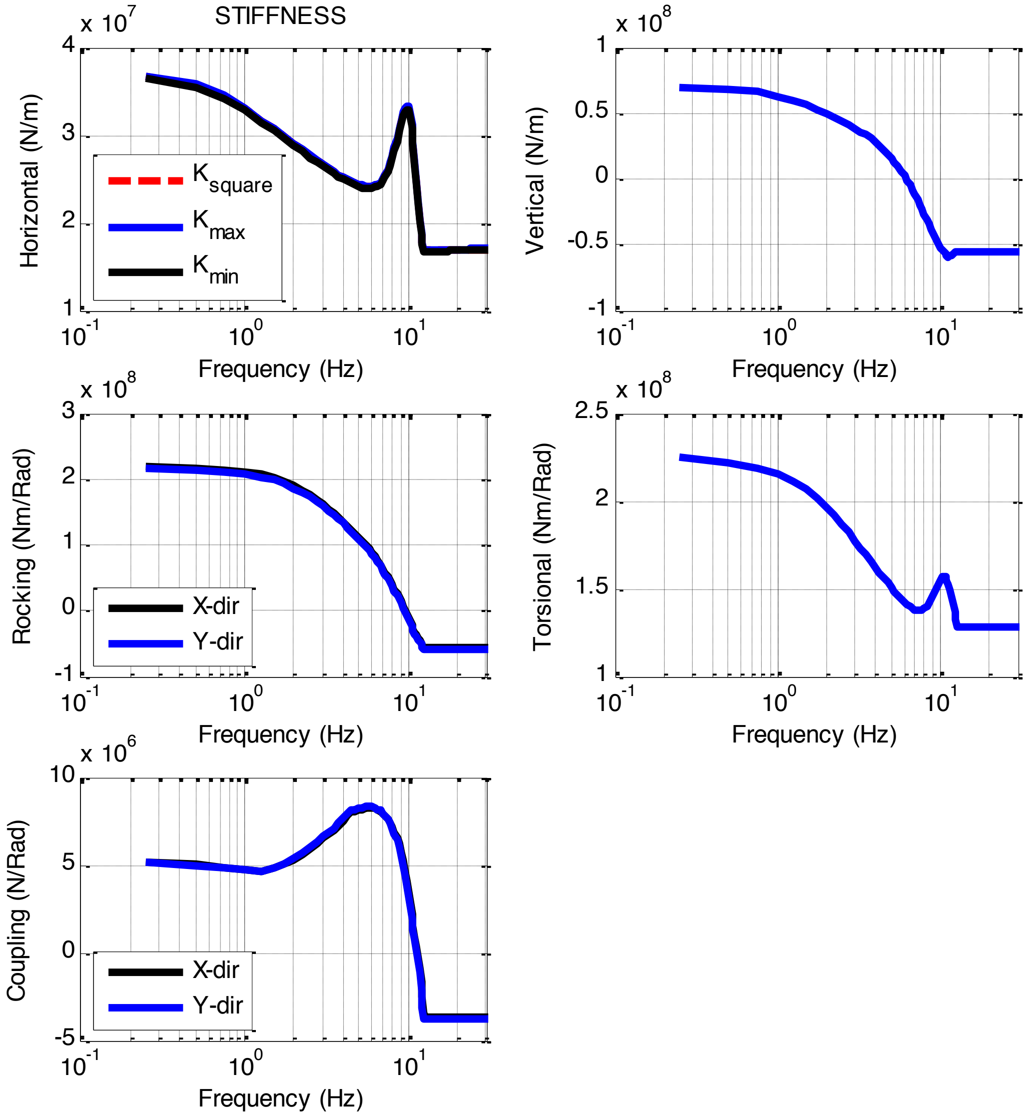


Figure 5.30: Detached Building on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

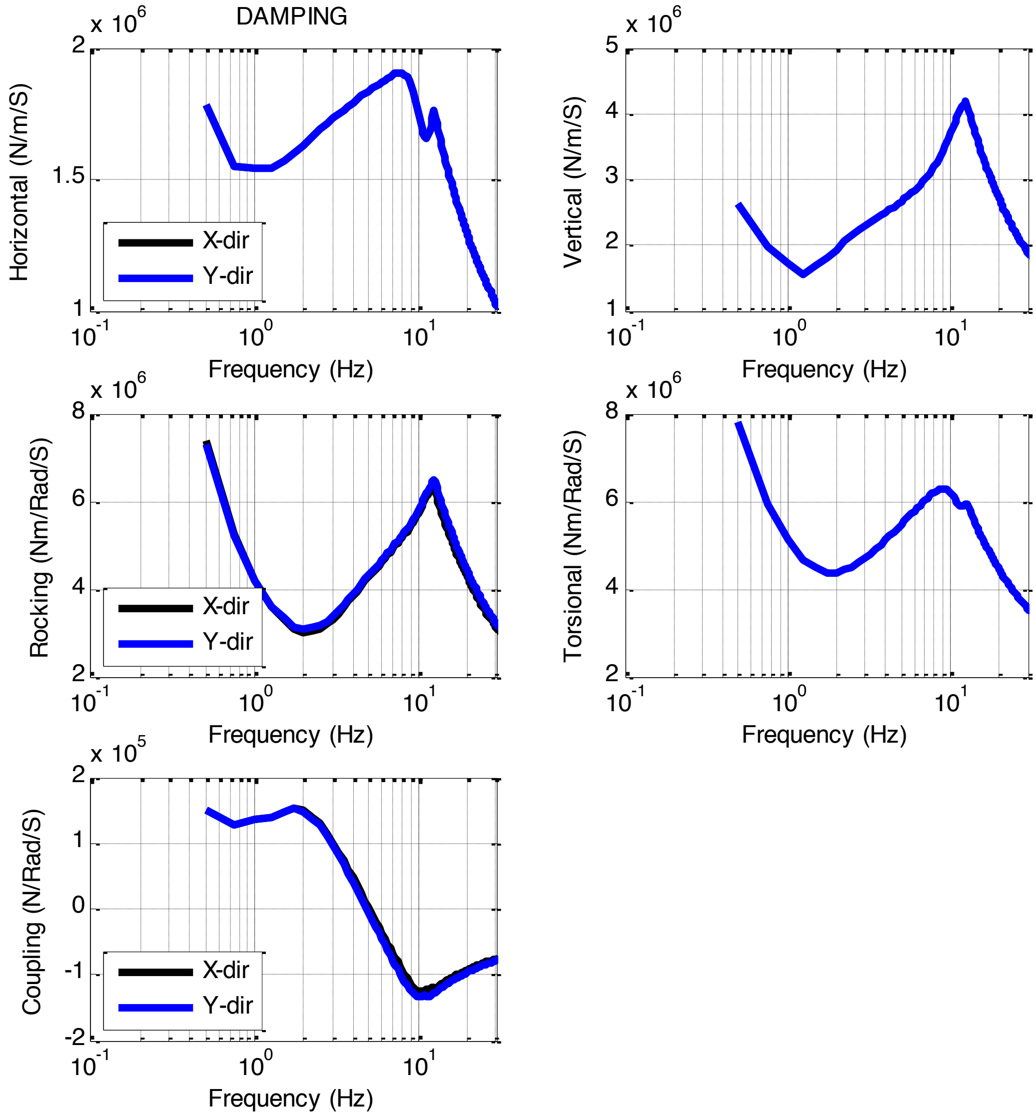


Figure 5.31: Detached Building on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

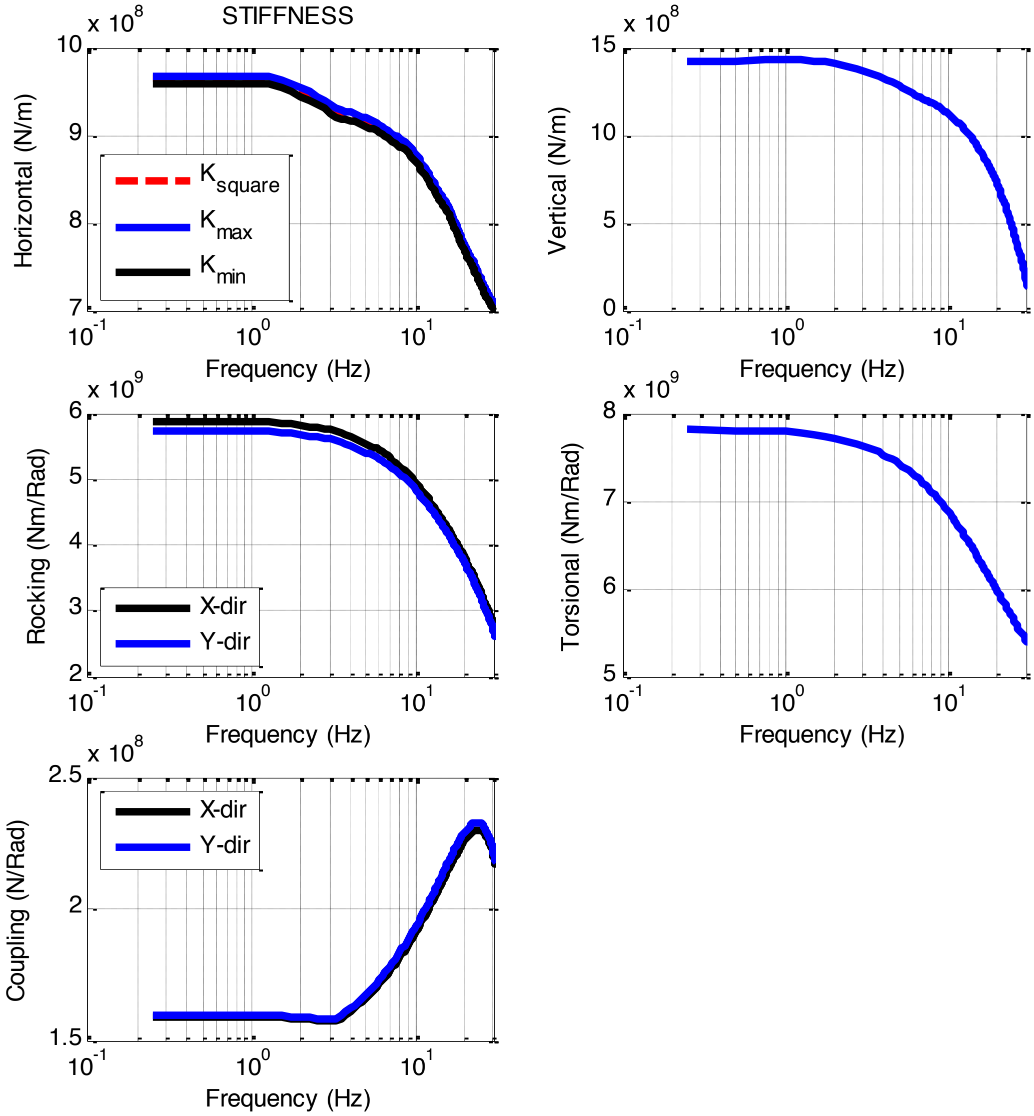


Figure 5.32: Detached Building on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

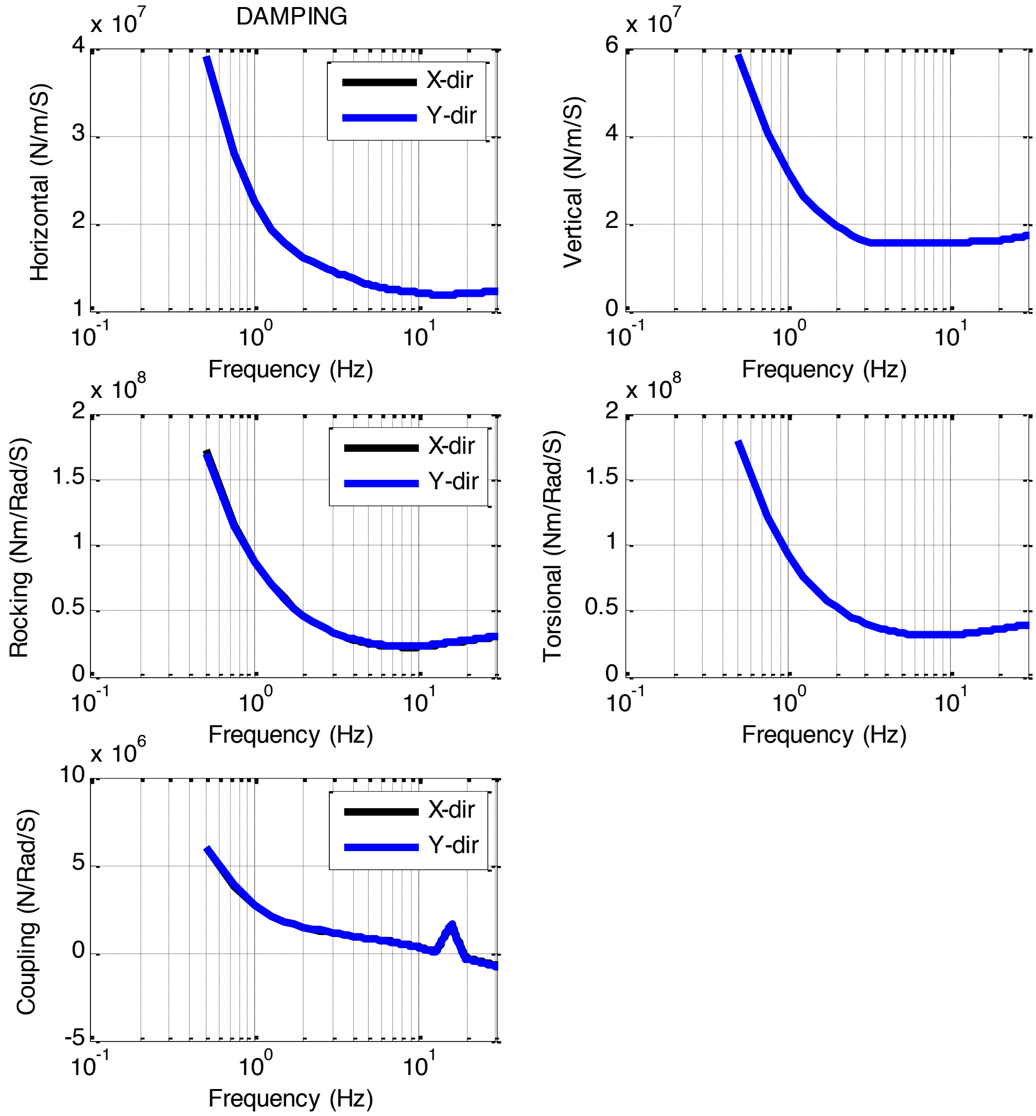


Figure 5.33: Detached Building on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

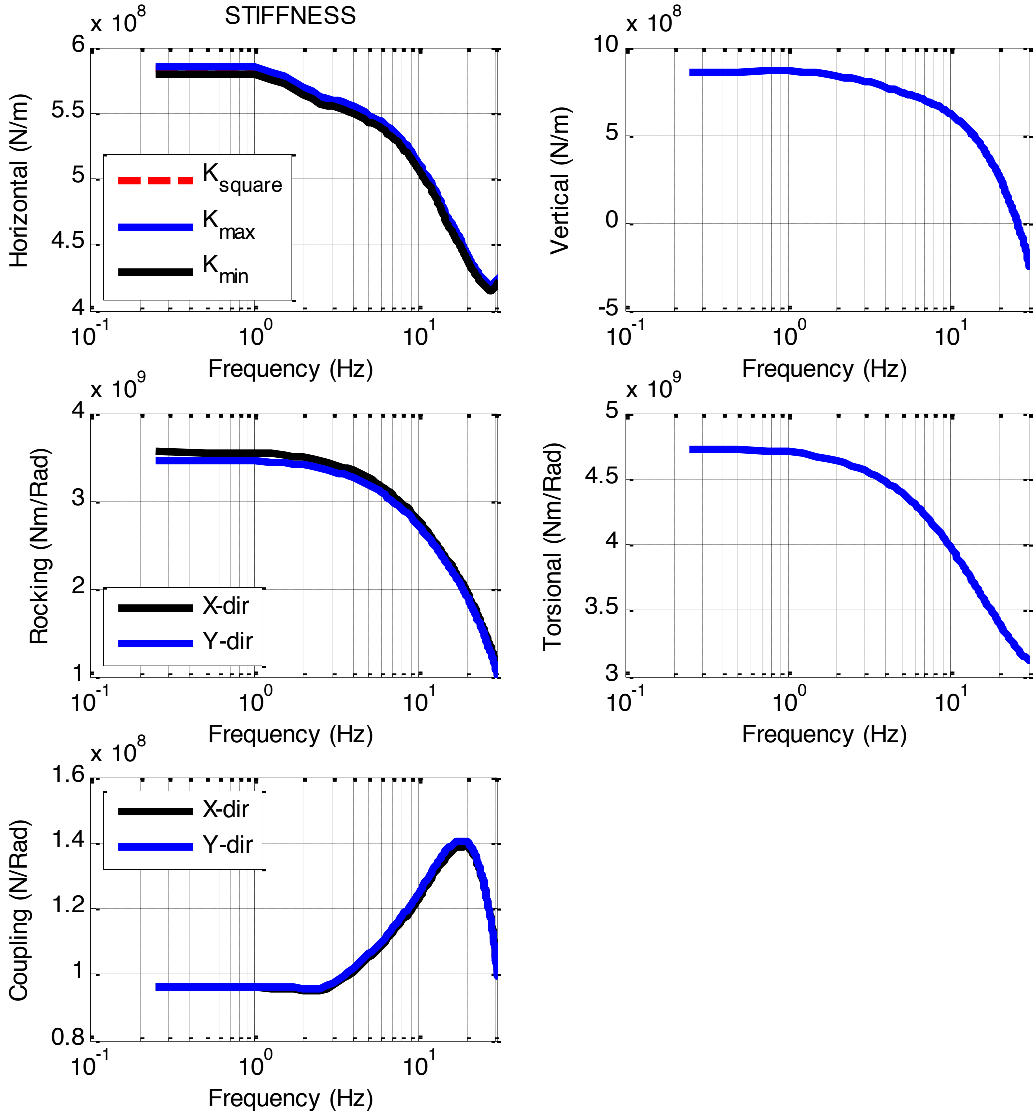


Figure 5.34: Detached Building on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

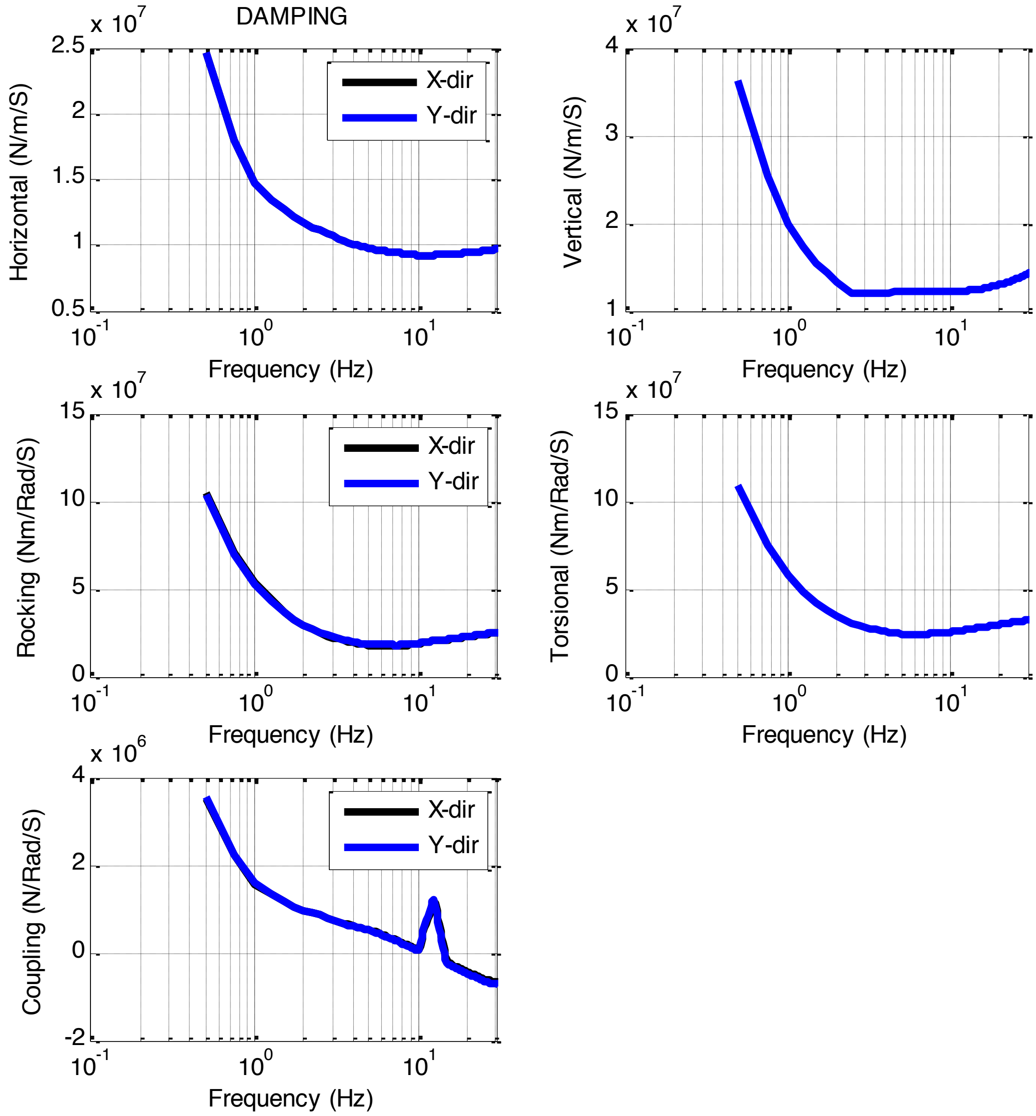


Figure 5.35: Detached Building on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

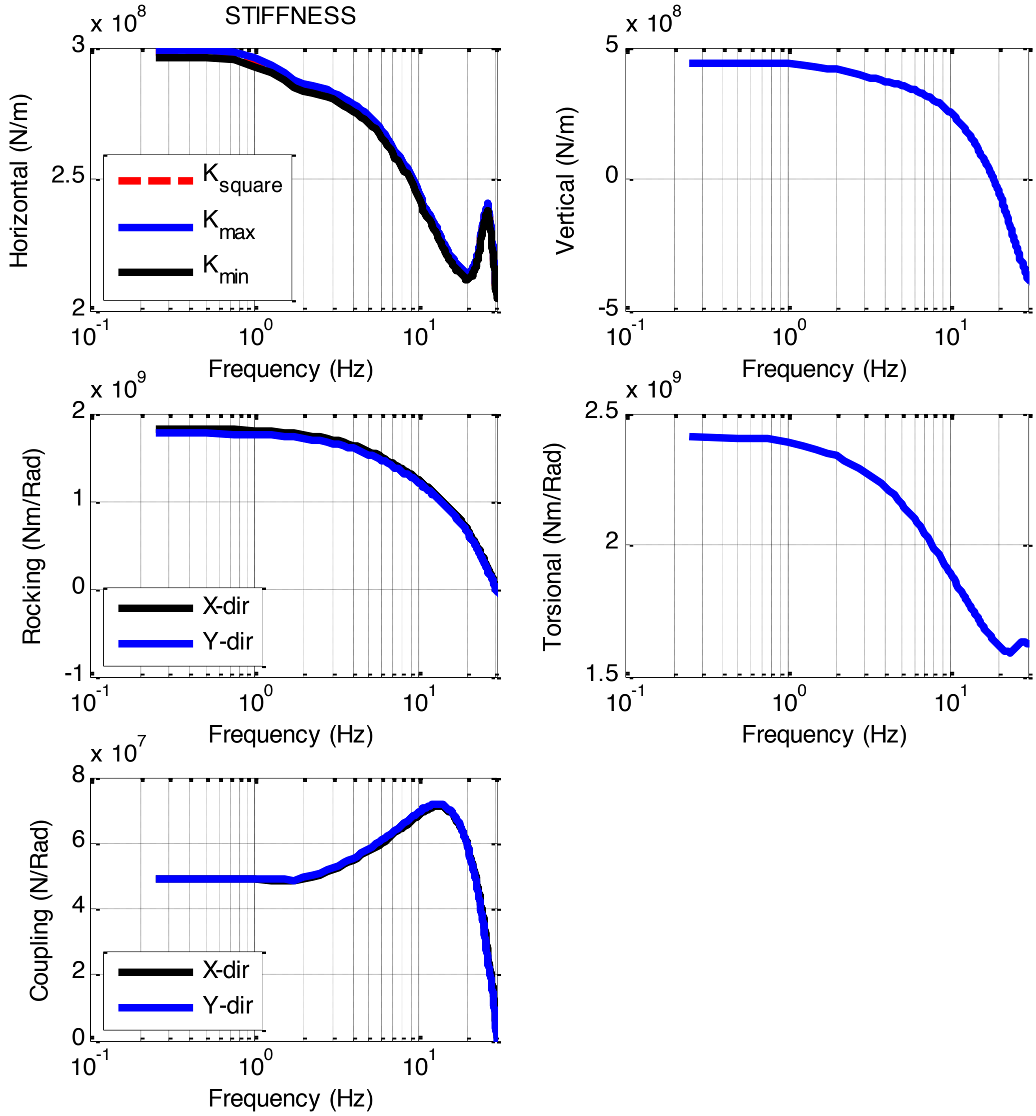


Figure 5.36: Detached Building on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

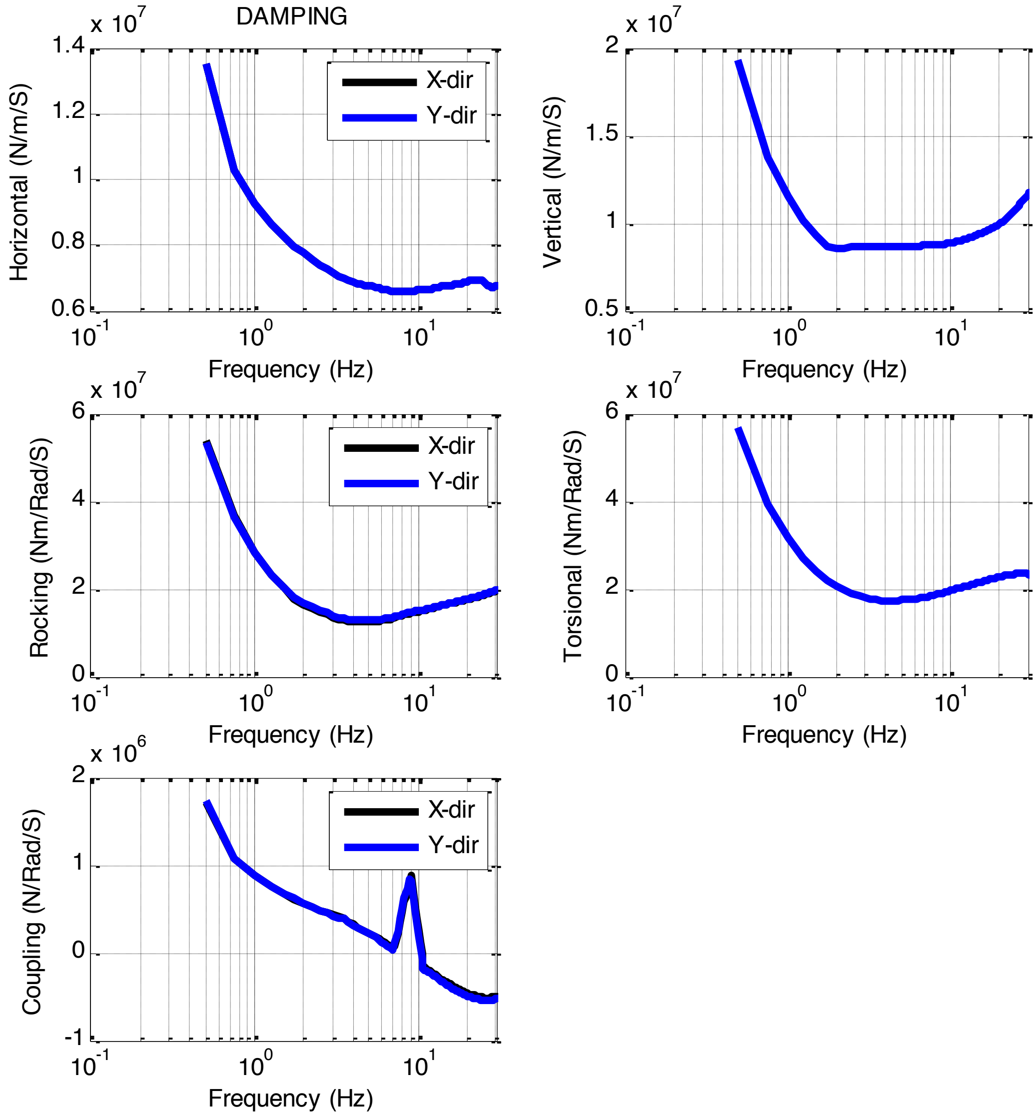


Figure 5.37: Detached Building on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

5.2 Terraced building, 2 Units – Concrete foundations

Figure 5.38 shows the scheme of the foundations of the Terraced building typology with two units. Hereinafter there are the impedance functions (in terms of frequency dependent stiffness and damping) of the building taking into account the three reference soil profiles defined in section 4.1.1 and the three scaling factors of section 4.1.2. The foundations characteristics are summarized in the following table.

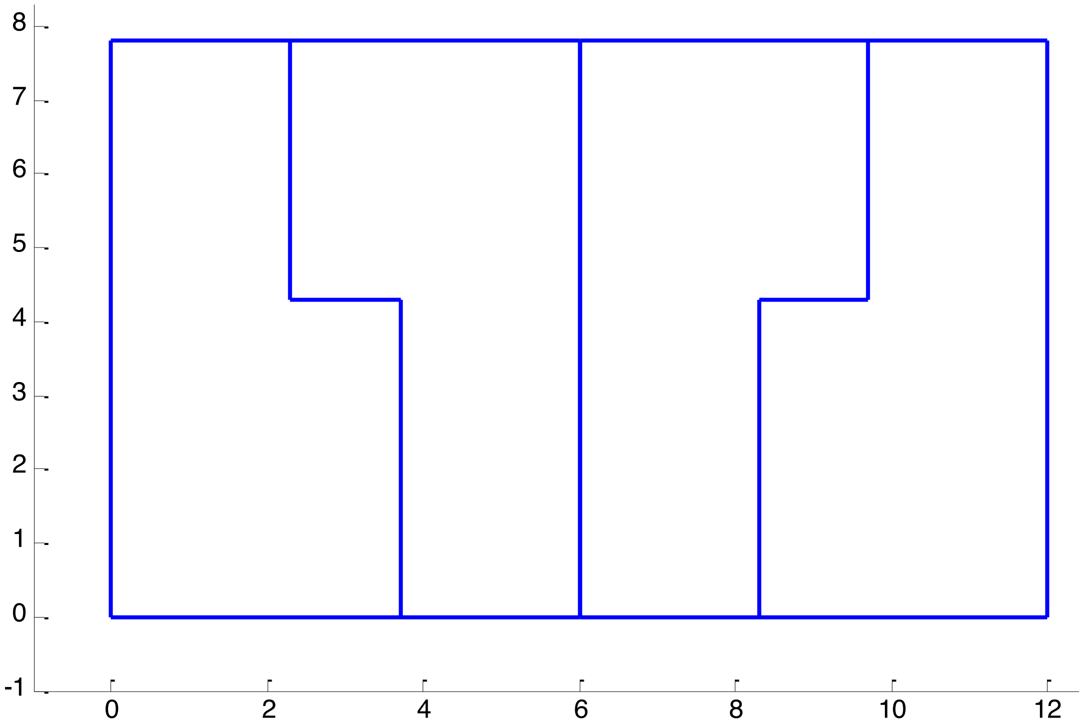


Figure 5.38: Terraced building, 2 units: schematic position of beam foundations

Table 5.3: Foundations characteristics of Terraced building, 2 Units – Concrete foundations

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m²]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m²]	I_{yy} [kg m²]	I_{zz} [kg m²]	I_{xy} [kg m²]	I_{xz} [kg m²]	I_{yz} [kg m²]
12	7.8	0.33	24.3	6.11	3.97	19.2e3	157.8e3	266.0e3	423.5e3	1.2e3	0	0

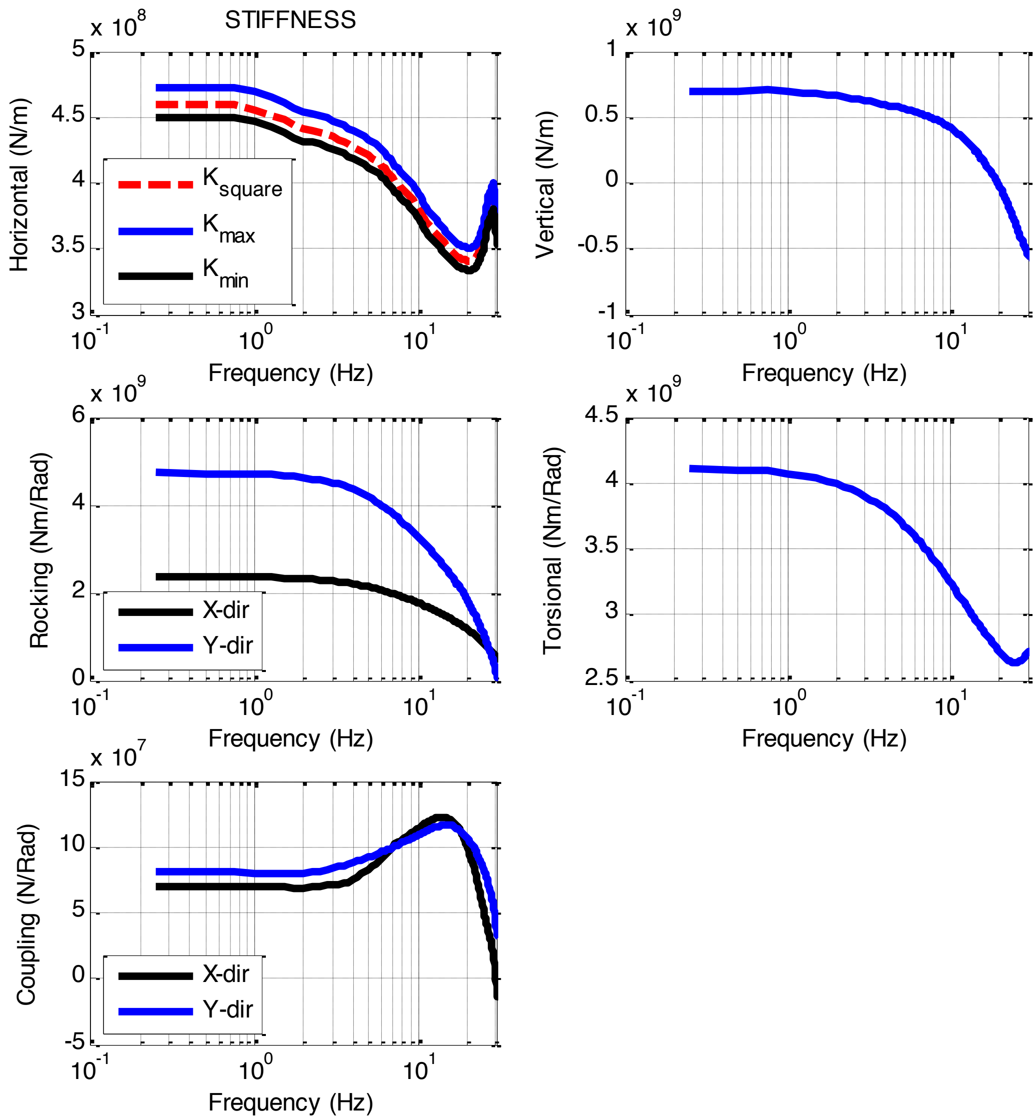


Figure 5.39: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: STIFFNESS

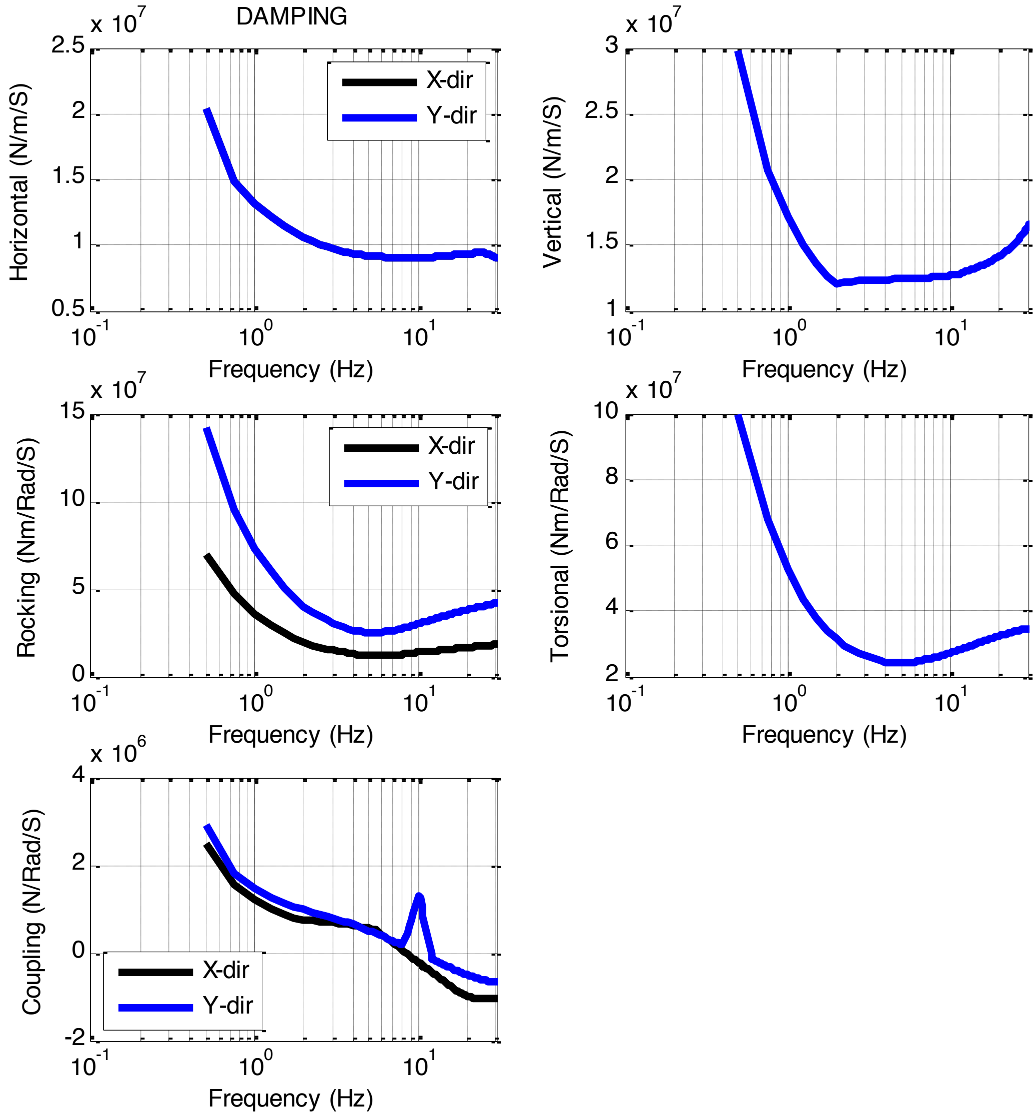


Figure 5.40: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: DAMPING

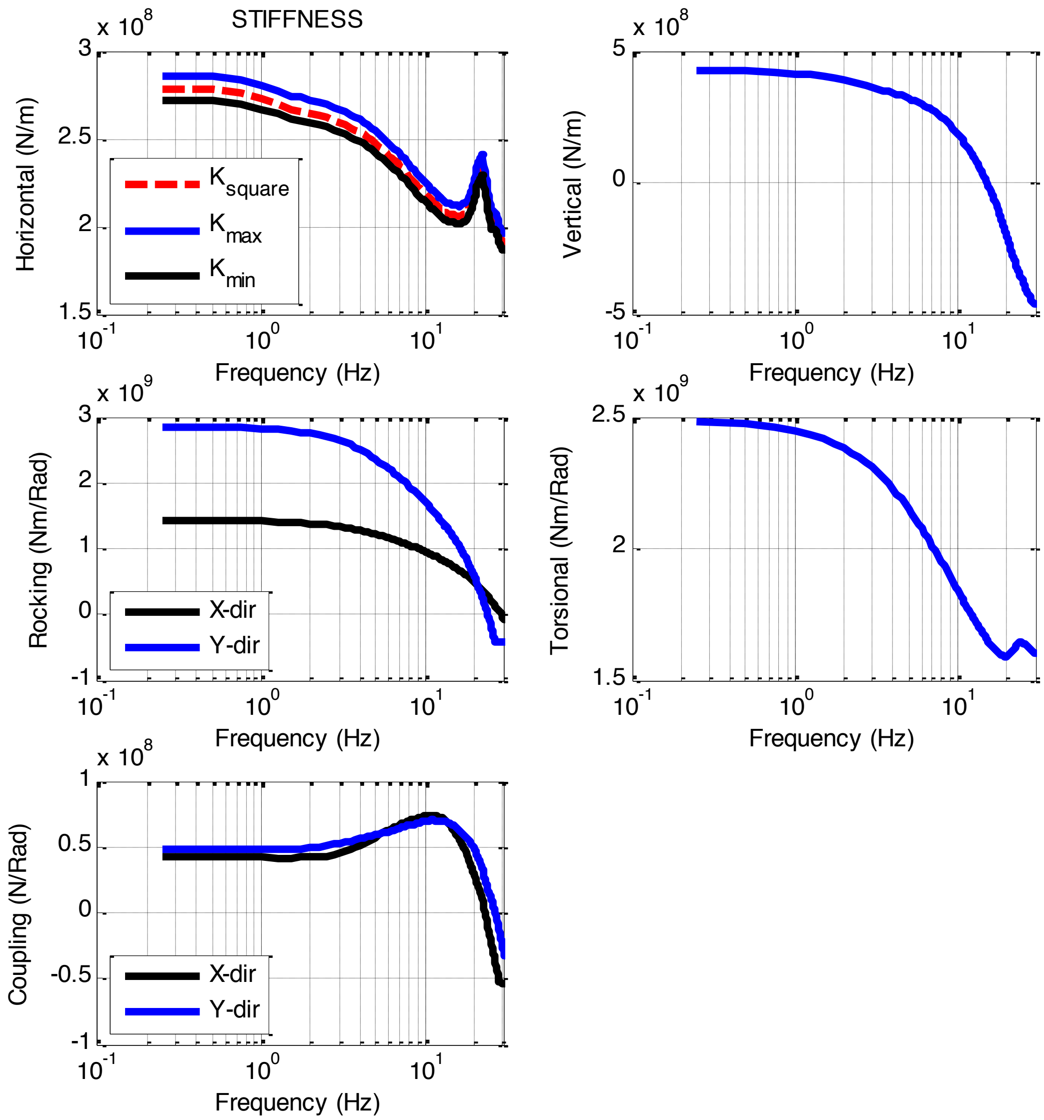


Figure 5.41: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: STIFFNESS

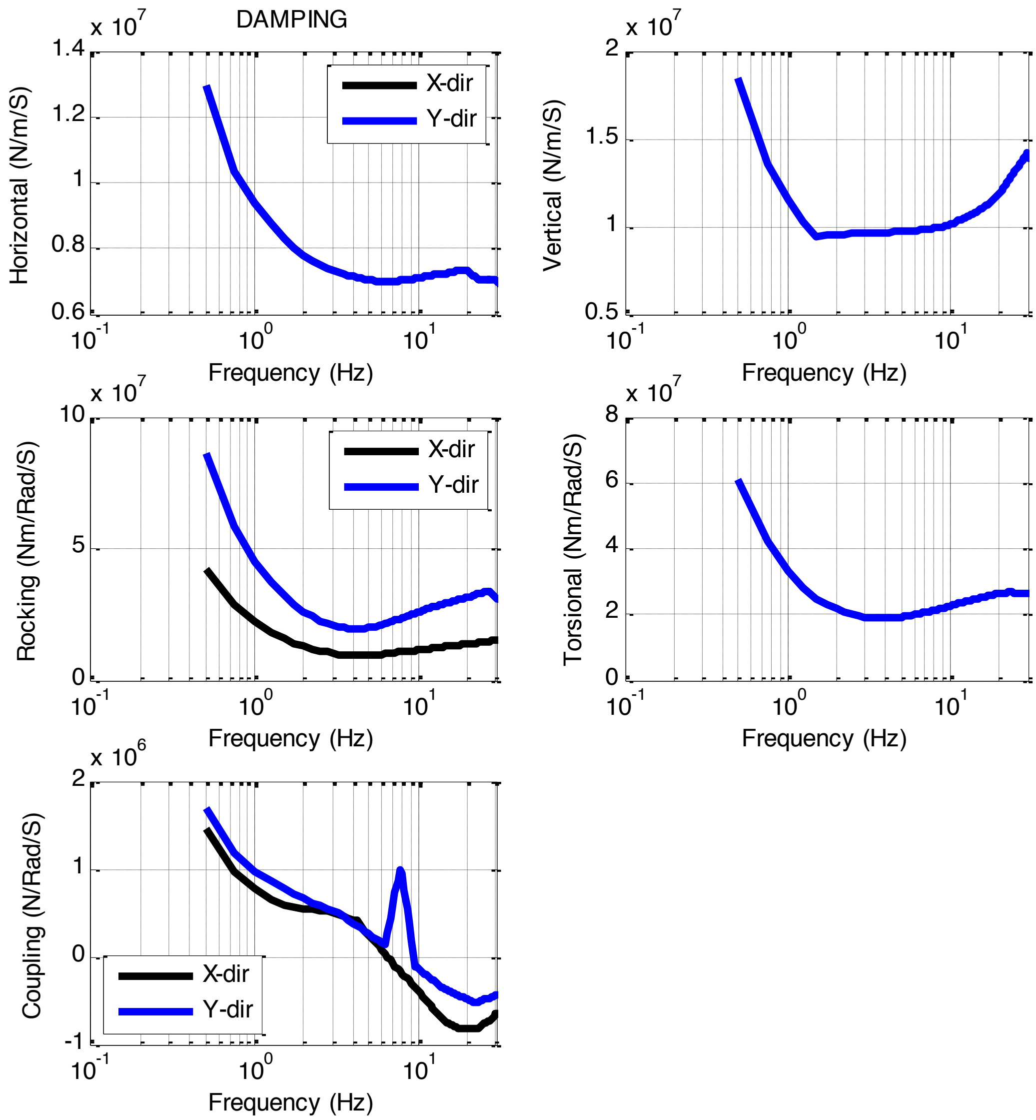


Figure 5.42: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: DAMPING

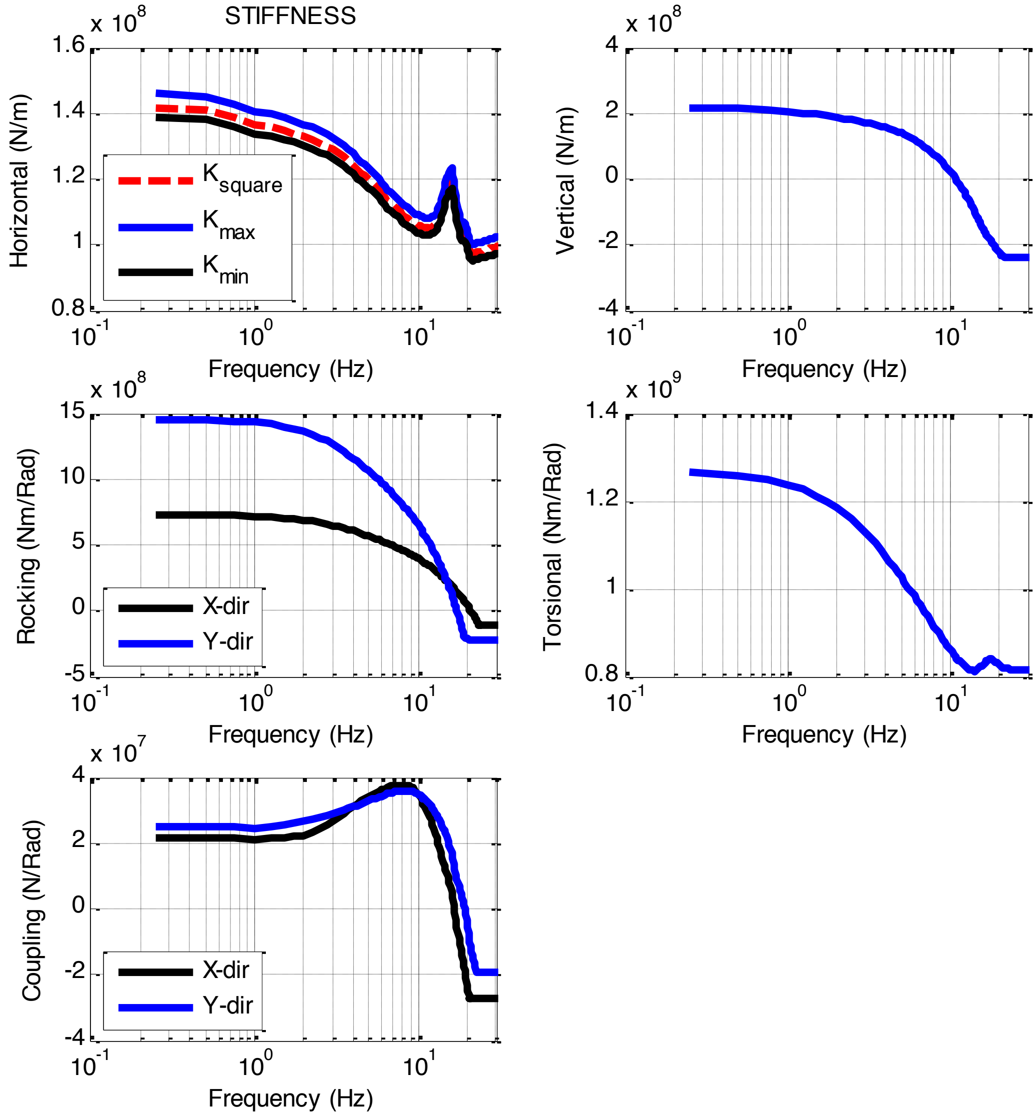


Figure 5.43: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: STIFFNESS

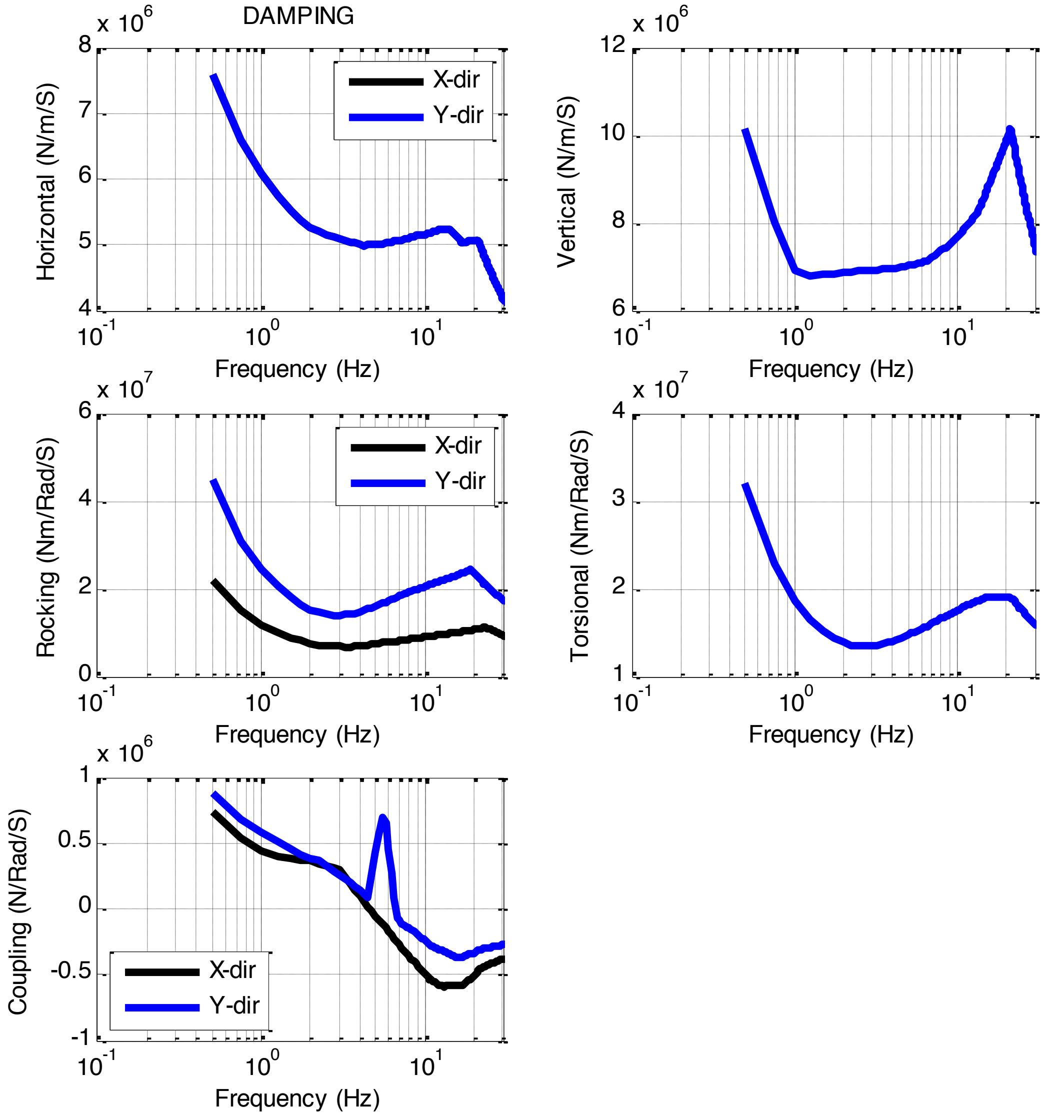


Figure 5.44: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: DAMPING

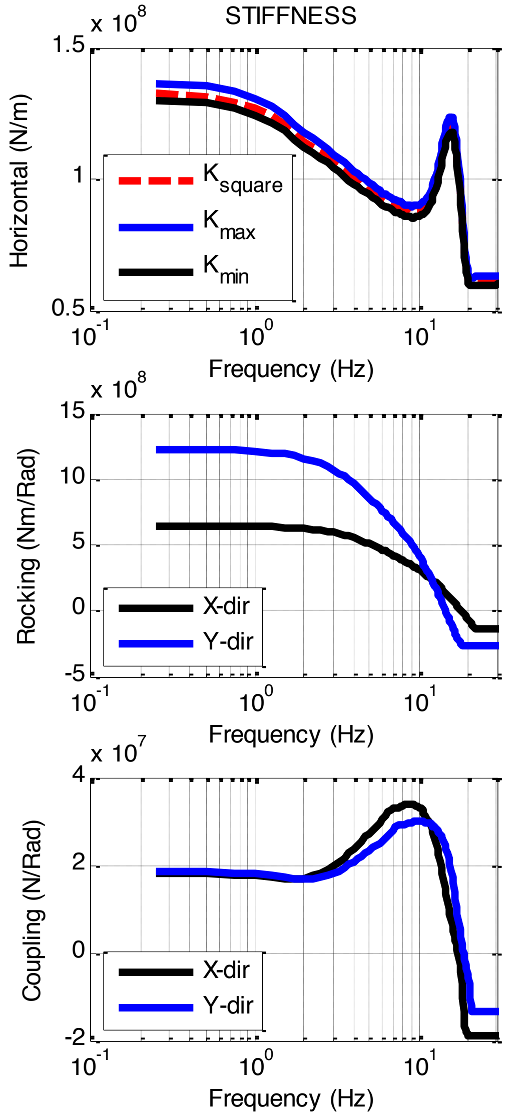


Figure 5.45: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

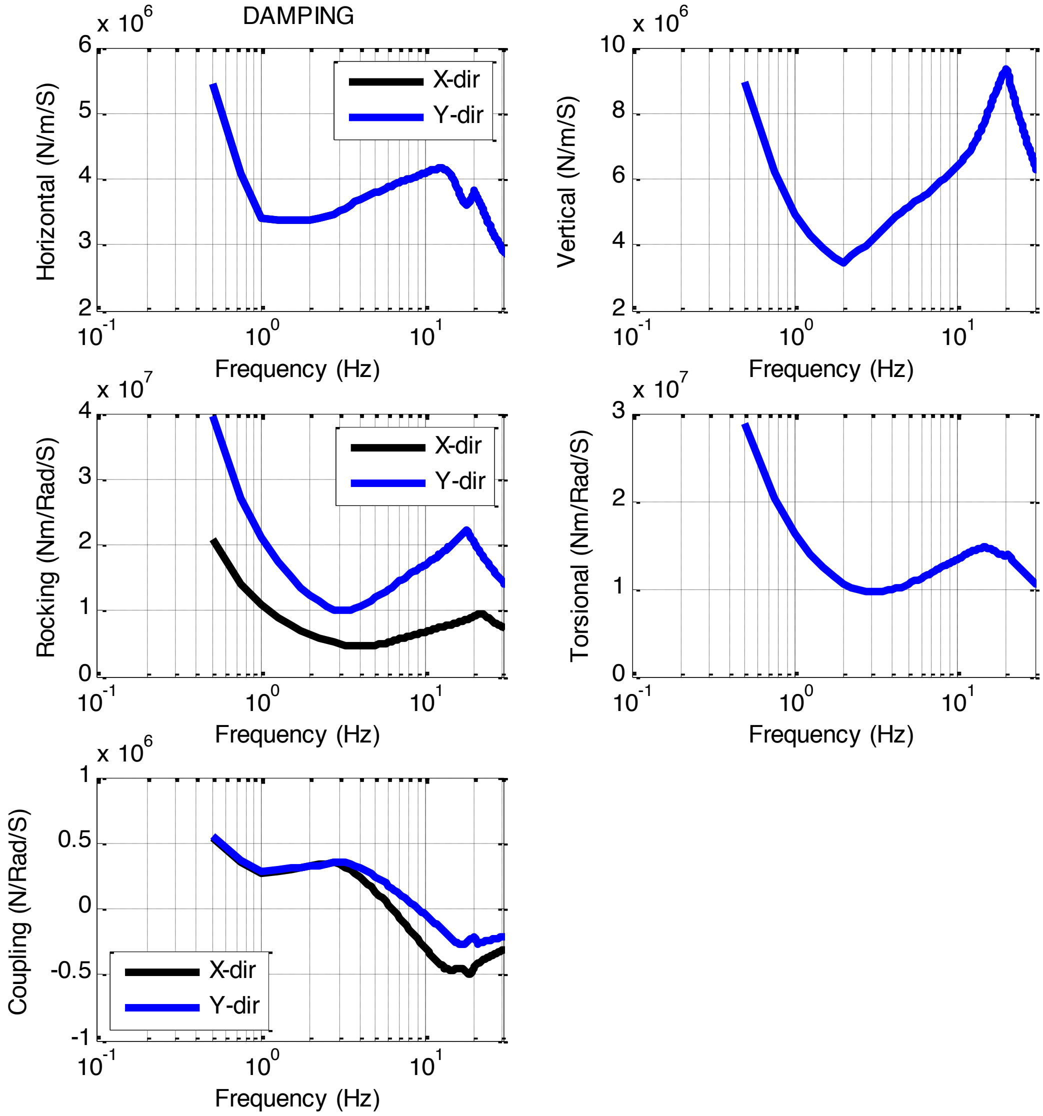


Figure 5.46: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

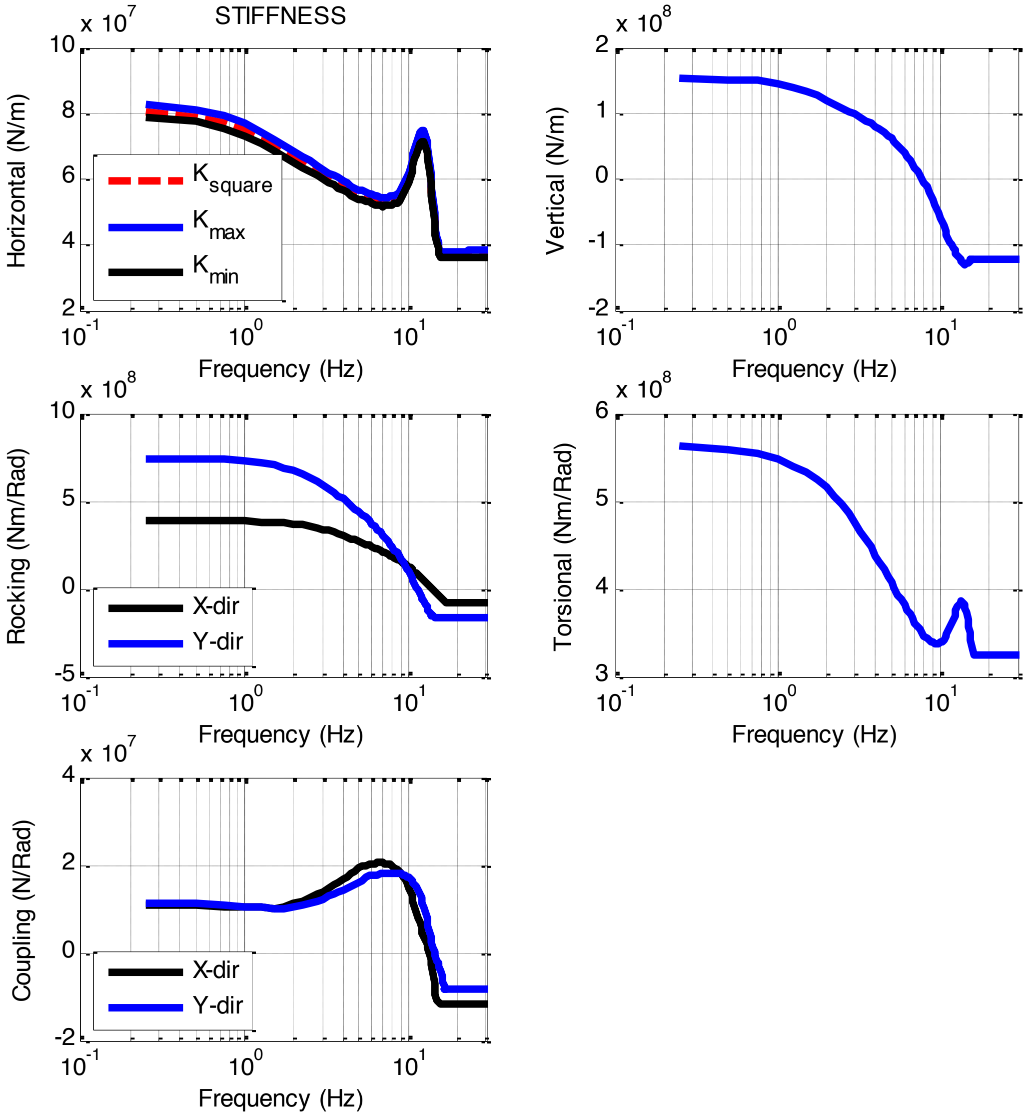


Figure 5.47: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

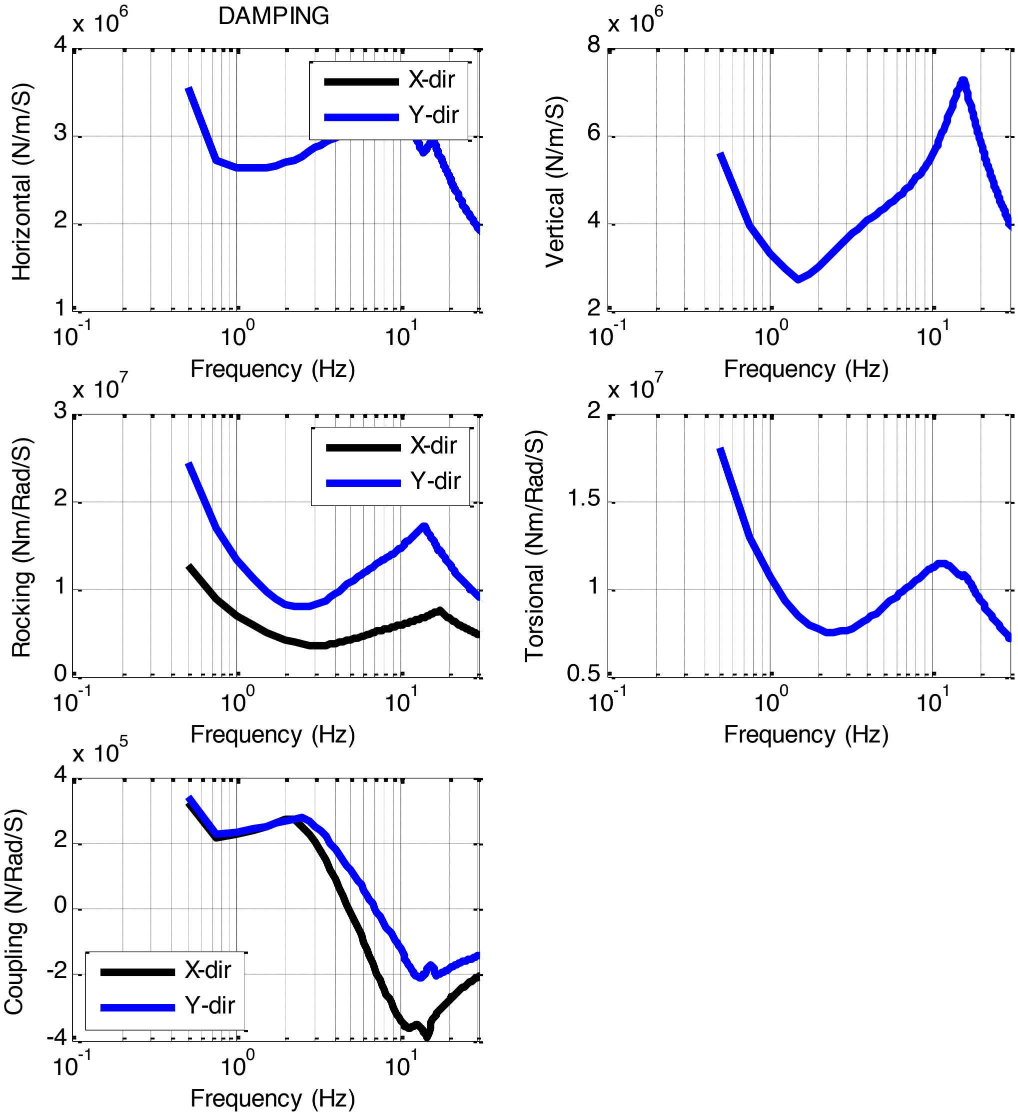


Figure 5.48: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

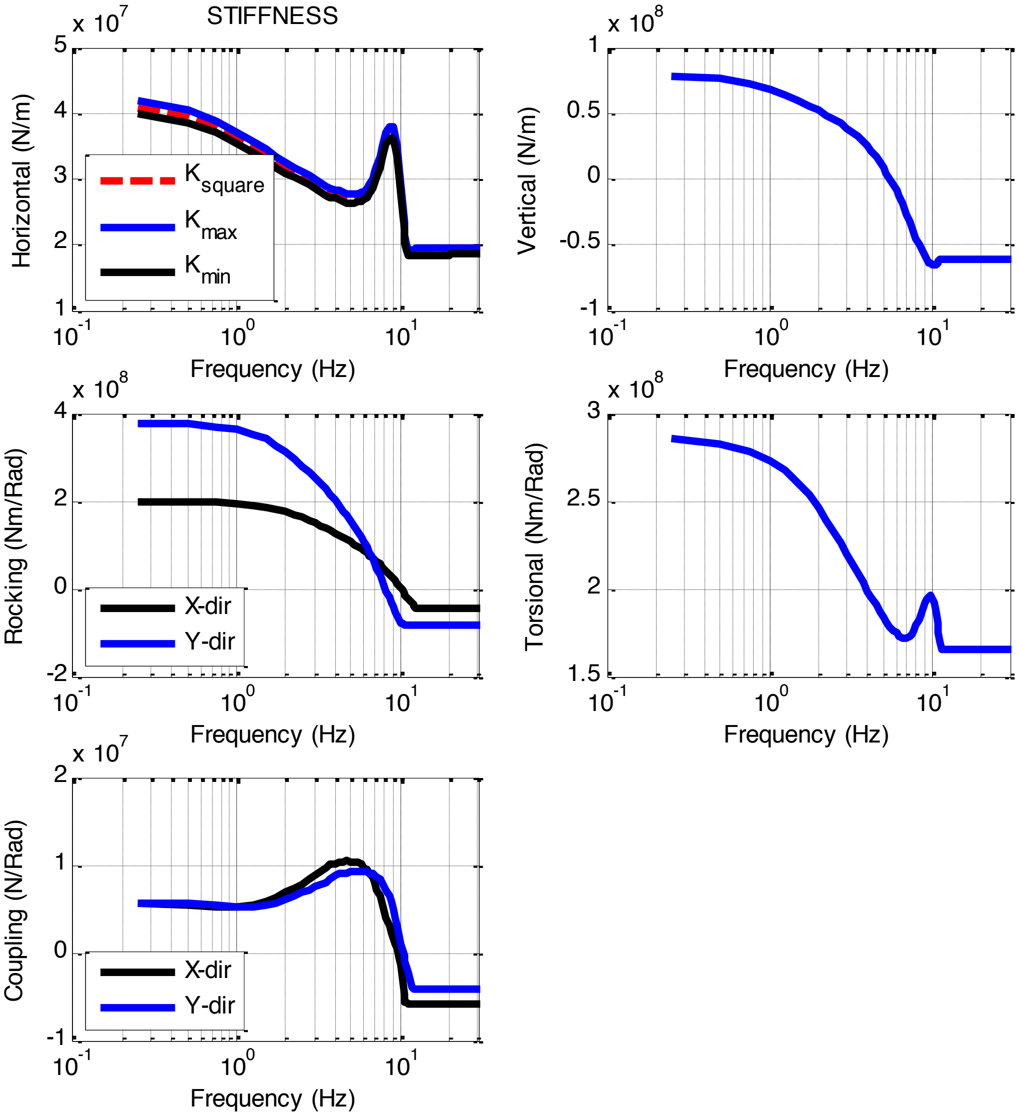


Figure 5.49: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

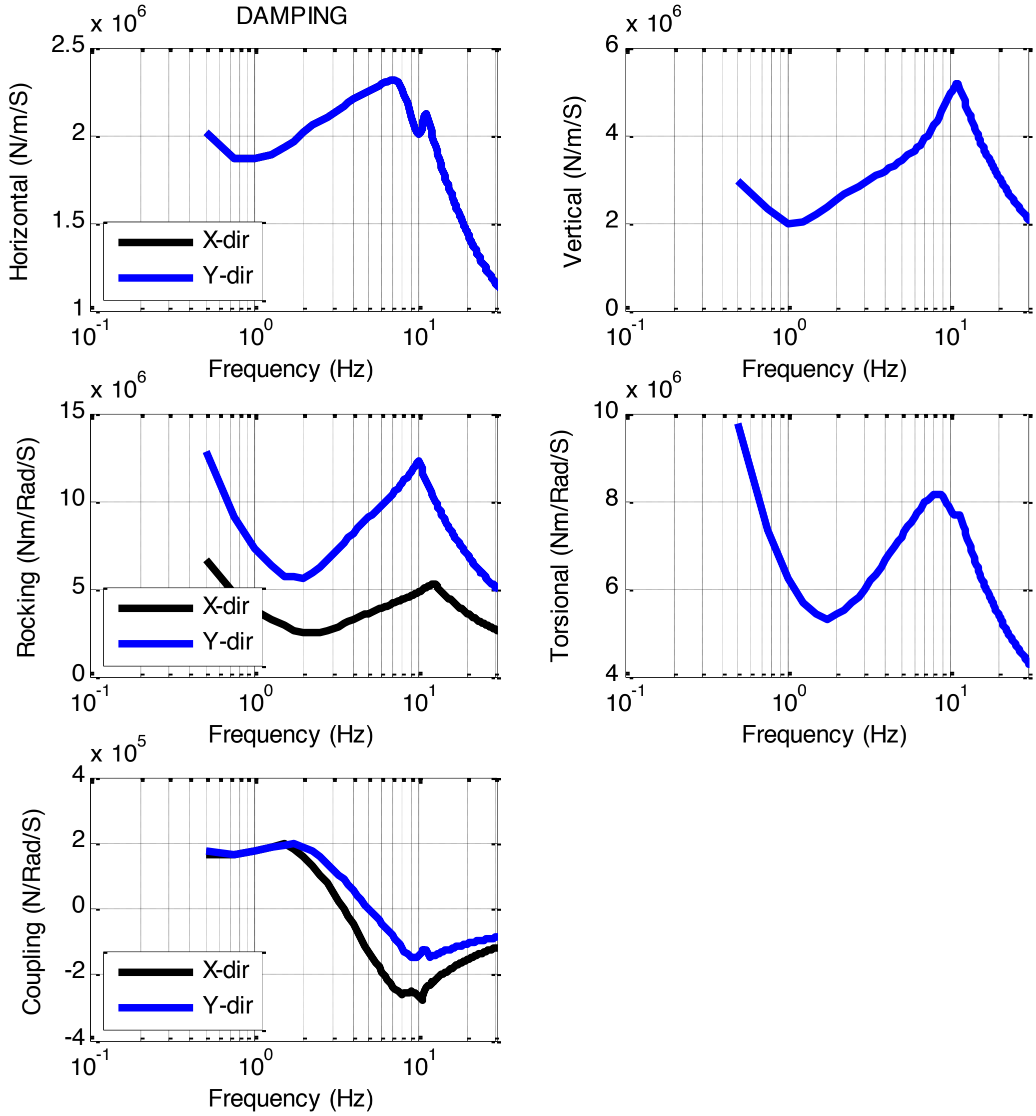


Figure 5.50: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

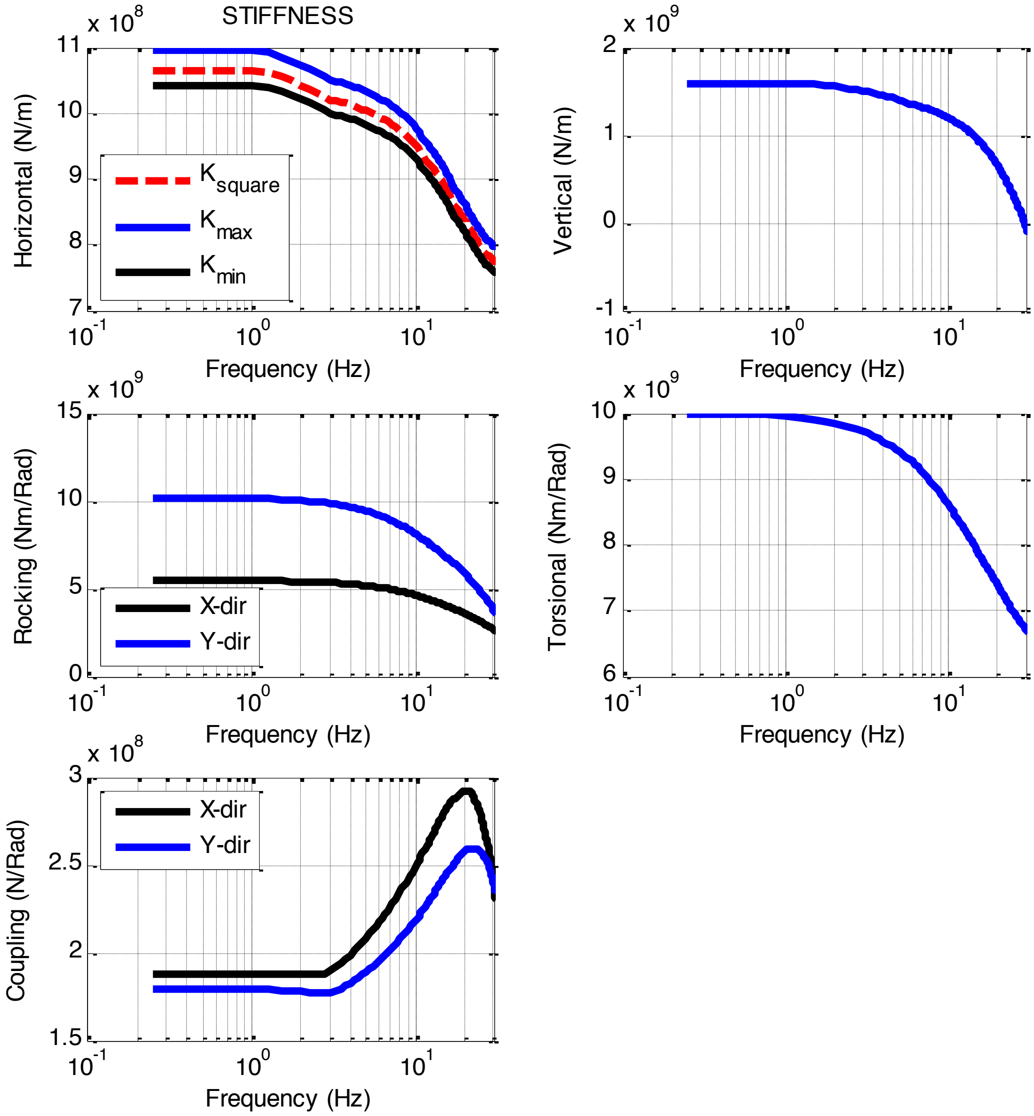


Figure 5.51: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

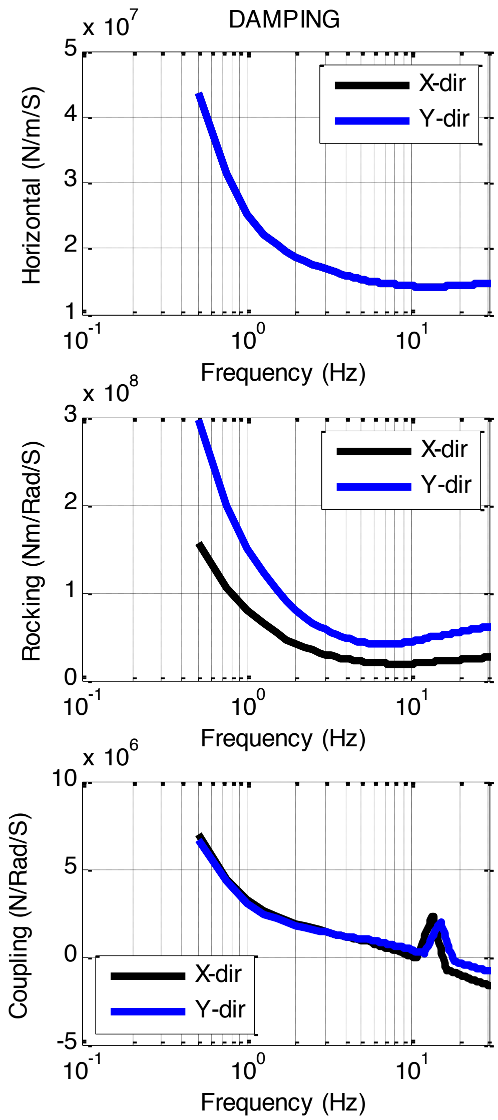


Figure 5.52: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

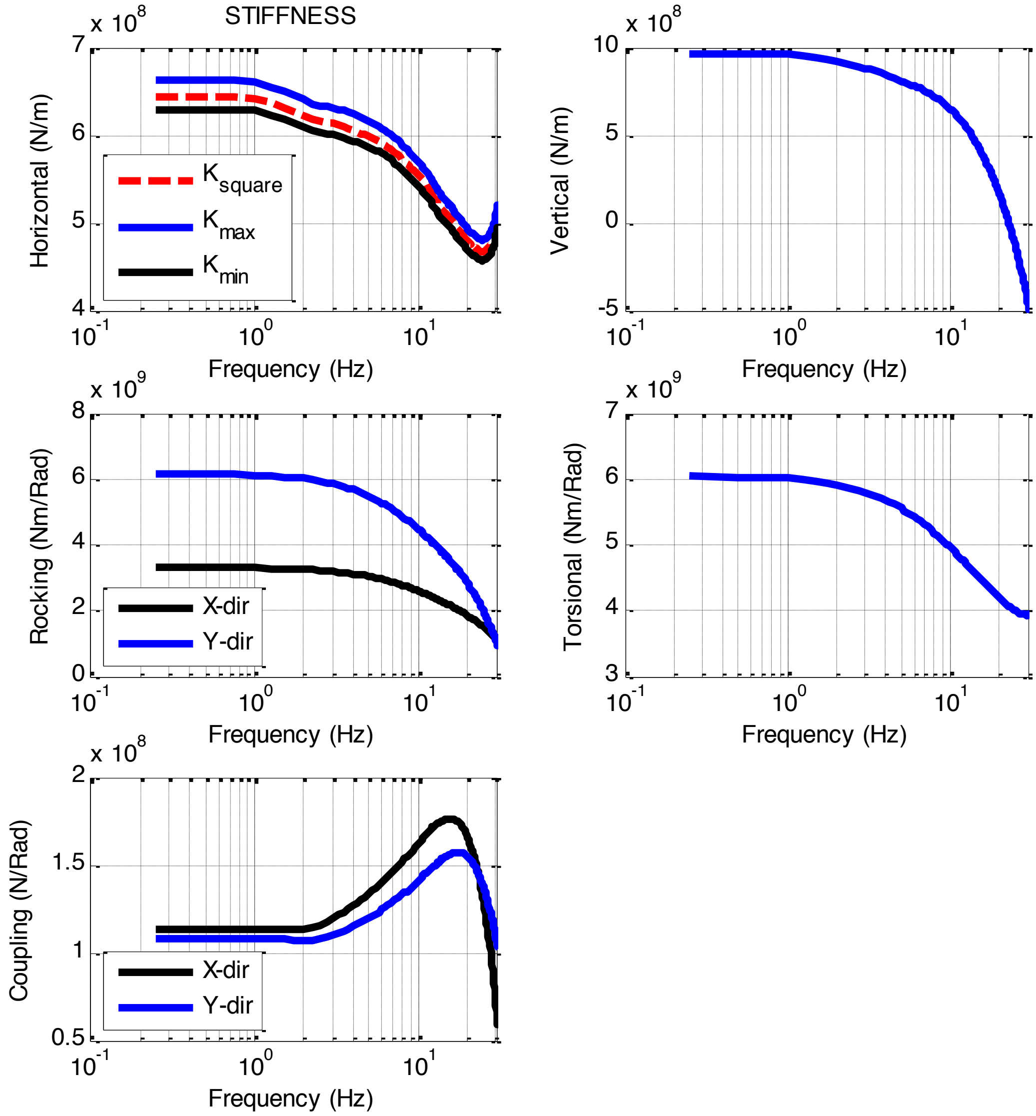


Figure 5.53: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

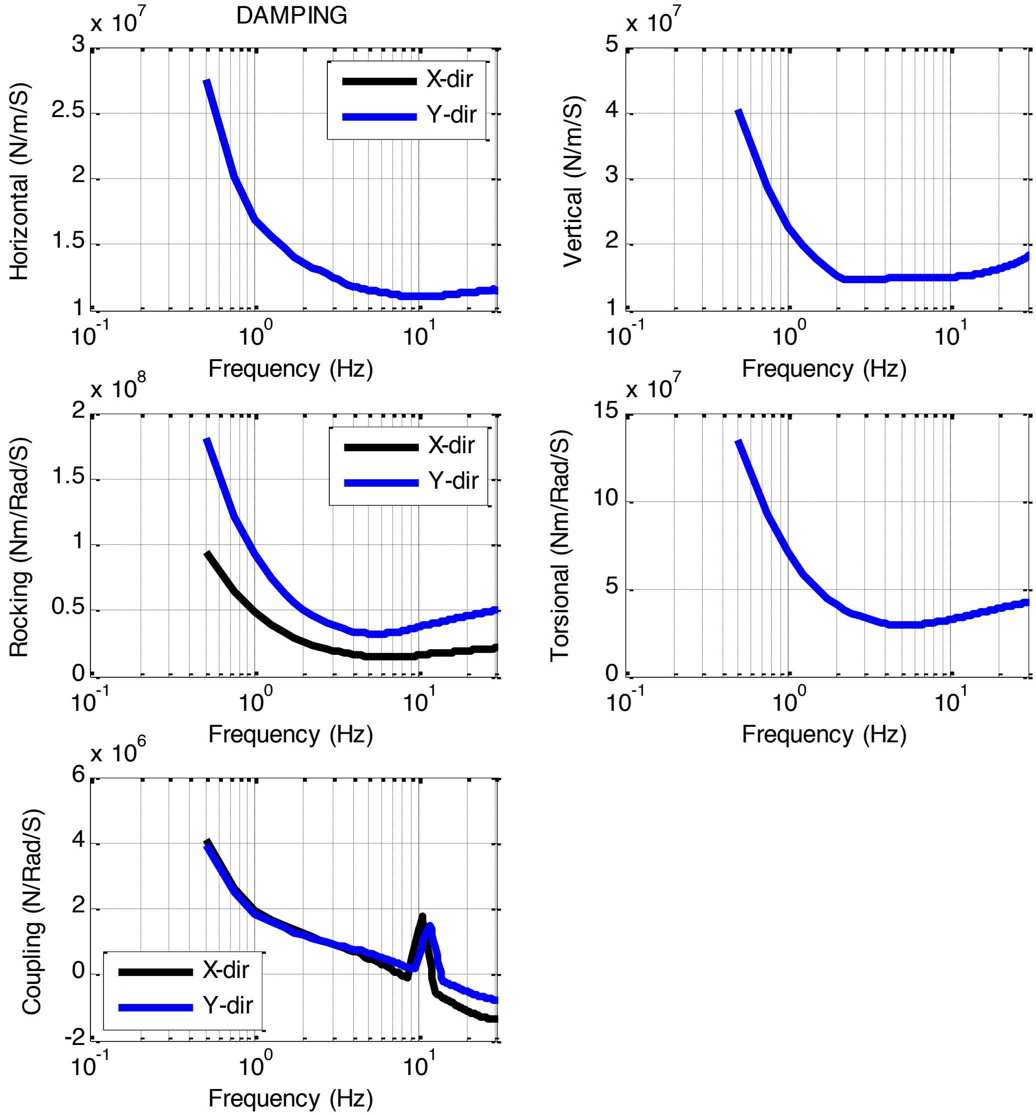


Figure 5.54: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

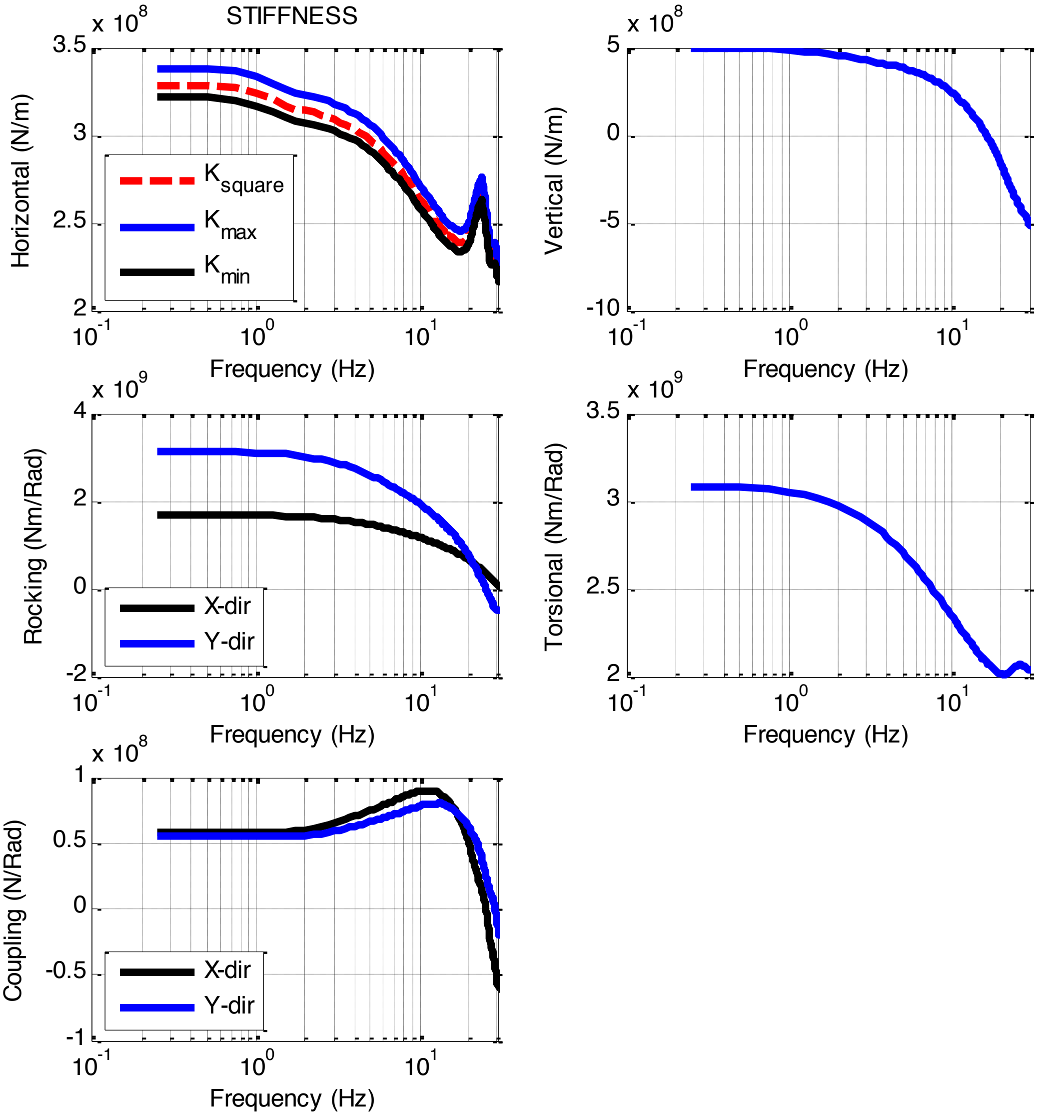


Figure 5.55: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

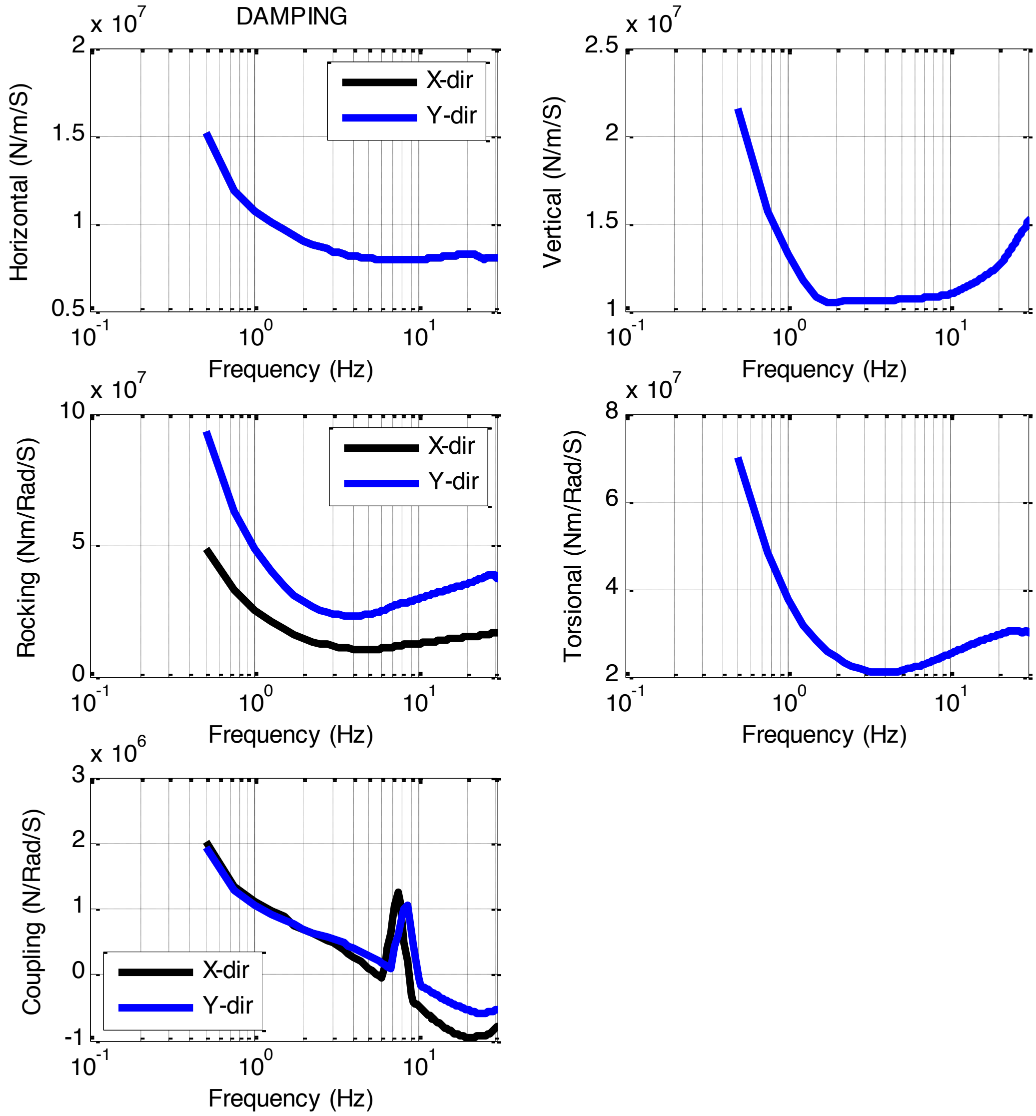


Figure 5.56: Terraced Building with 2 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

5.3 Terraced building, 4 Units

Figure 5.57 shows the scheme of the foundations of the Terraced building typology with 4 units. The following sections show the impedance functions (in terms of frequency dependent stiffness and damping) of the building taking into account the three reference soil profiles defined in section 4.1.1 and the three scaling factors of section 4.1.2. The foundations characteristics are summarized in the following tables.

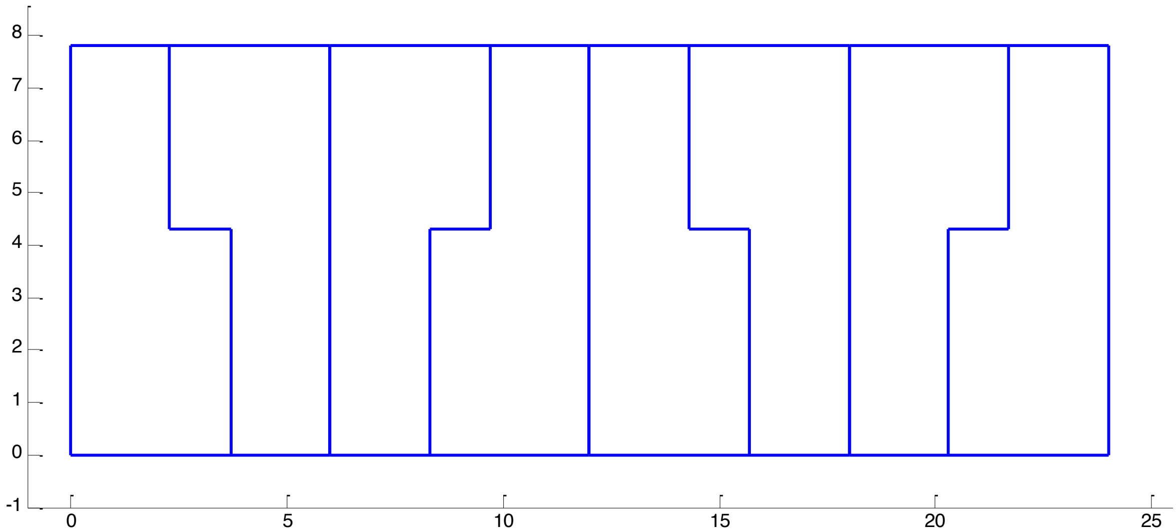


Figure 5.57: Terraced building, 4 units: schematic position of beam foundations

Table 5.4: Foundations characteristics of Terraced building, 4 Units – Masonry foundations

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m^2]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m^2]	I_{yy} [kg m^2]	I_{zz} [kg m^2]	I_{xy} [kg m^2]	I_{xz} [kg m^2]	I_{yz} [kg m^2]
24	7.8	0.26	81.0	15.78	5.13	40.6e3	332.9e3	2021.4e3	2353.8e3	2.579e3	0	0

Table 5.5: Foundations characteristics of Terraced building, 4 Units – Concrete foundations

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m^2]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m^2]	I_{yy} [kg m^2]	I_{zz} [kg m^2]	I_{xy} [kg m^2]	I_{xz} [kg m^2]	I_{yz} [kg m^2]
24	7.8	0.33	48.6	12.23	3.97	38.5e3	315.7e3	1917.3e3	2232.2e3	2.4e3	0	0

5.3.1 Masonry foundations

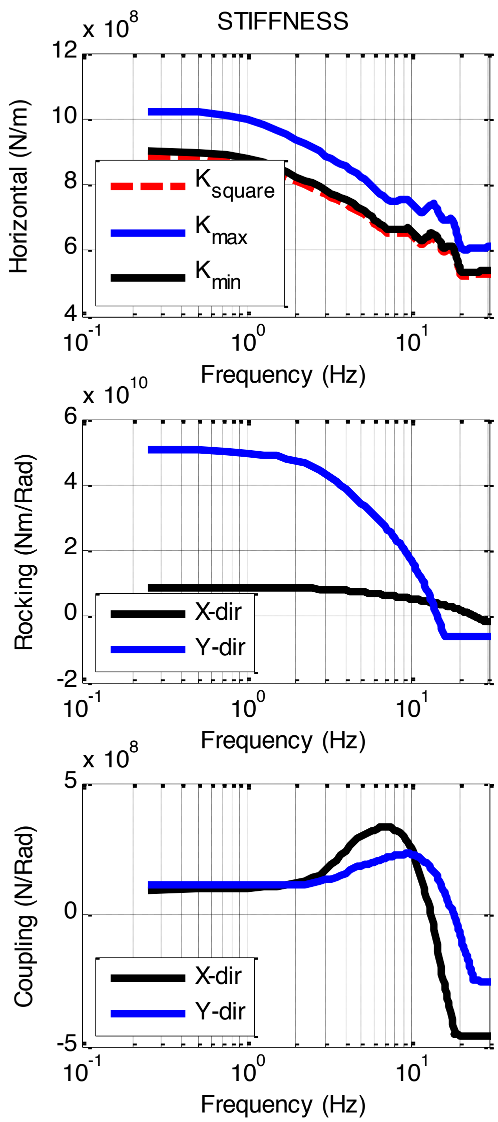


Figure 5.58: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF1: STIFFNESS

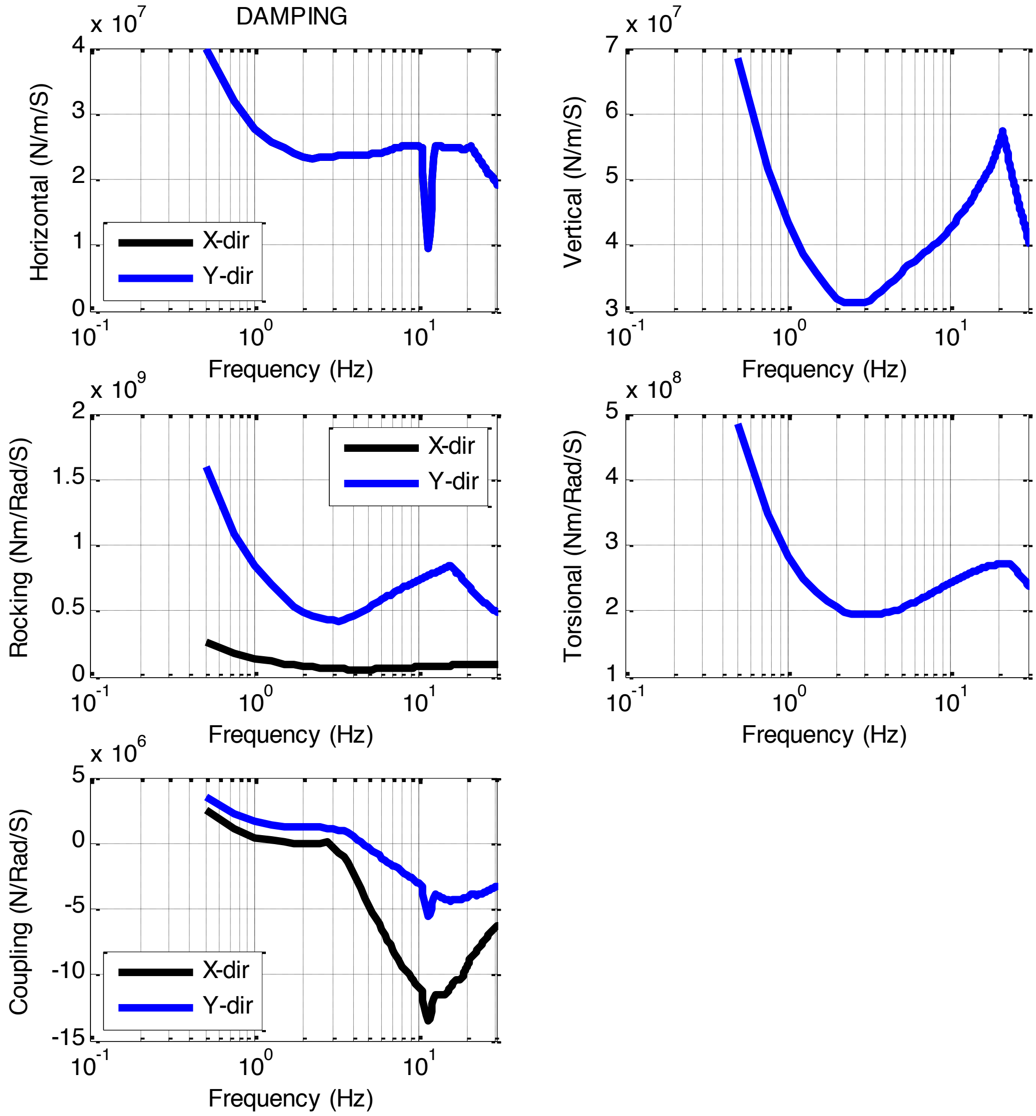


Figure 5.59: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF1: DAMPING

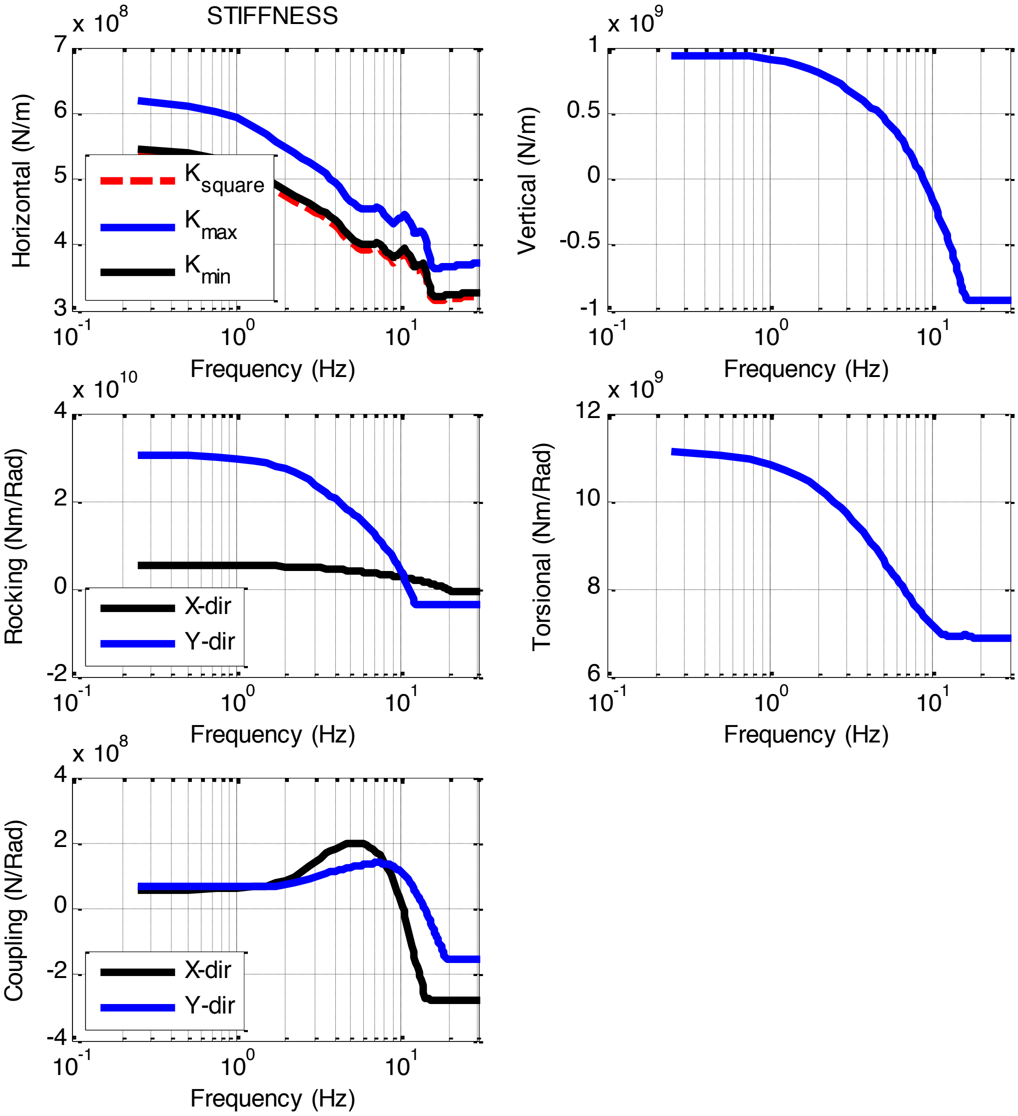


Figure 5.60: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF2: STIFFNESS

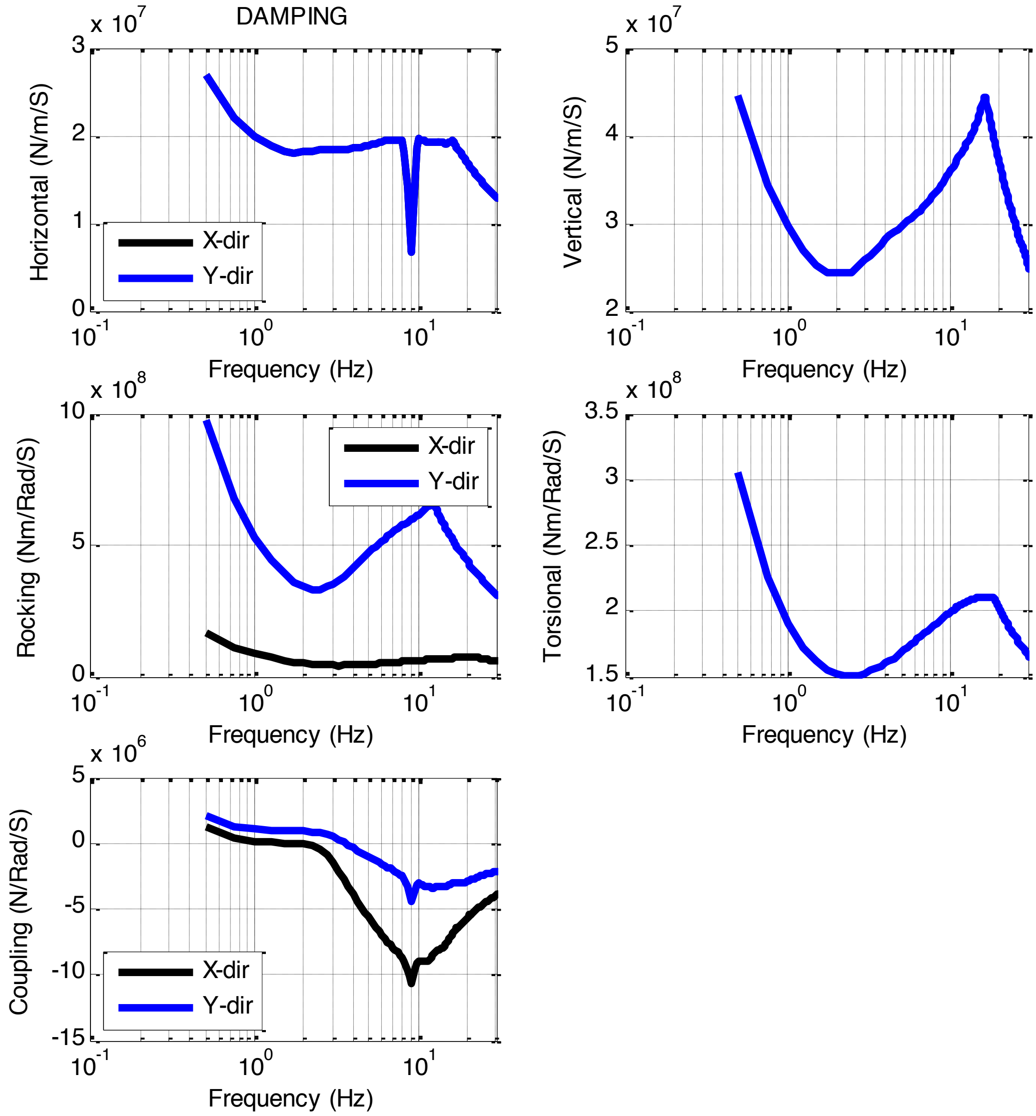


Figure 5.61: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF2: DAMPING

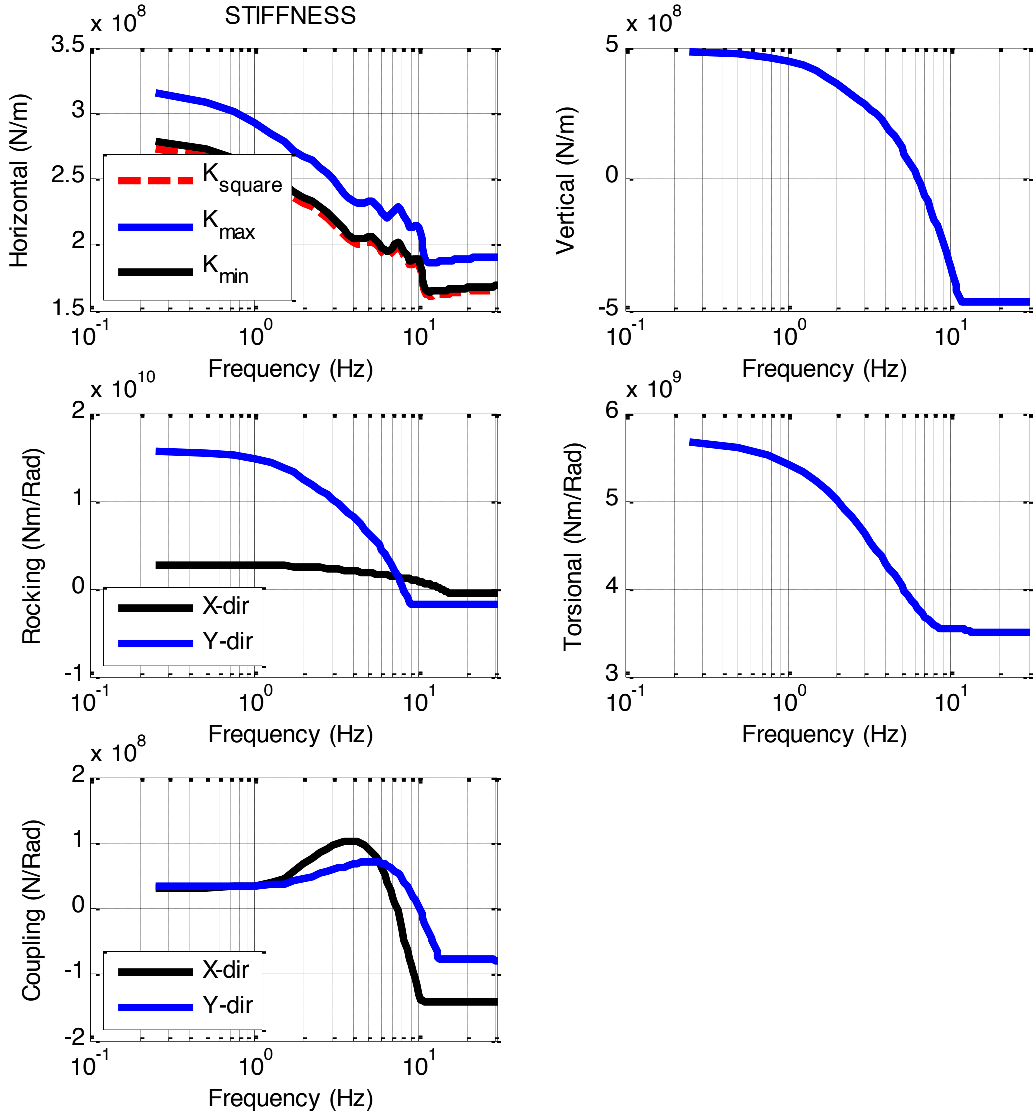


Figure 5.62: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF3: STIFFNESS

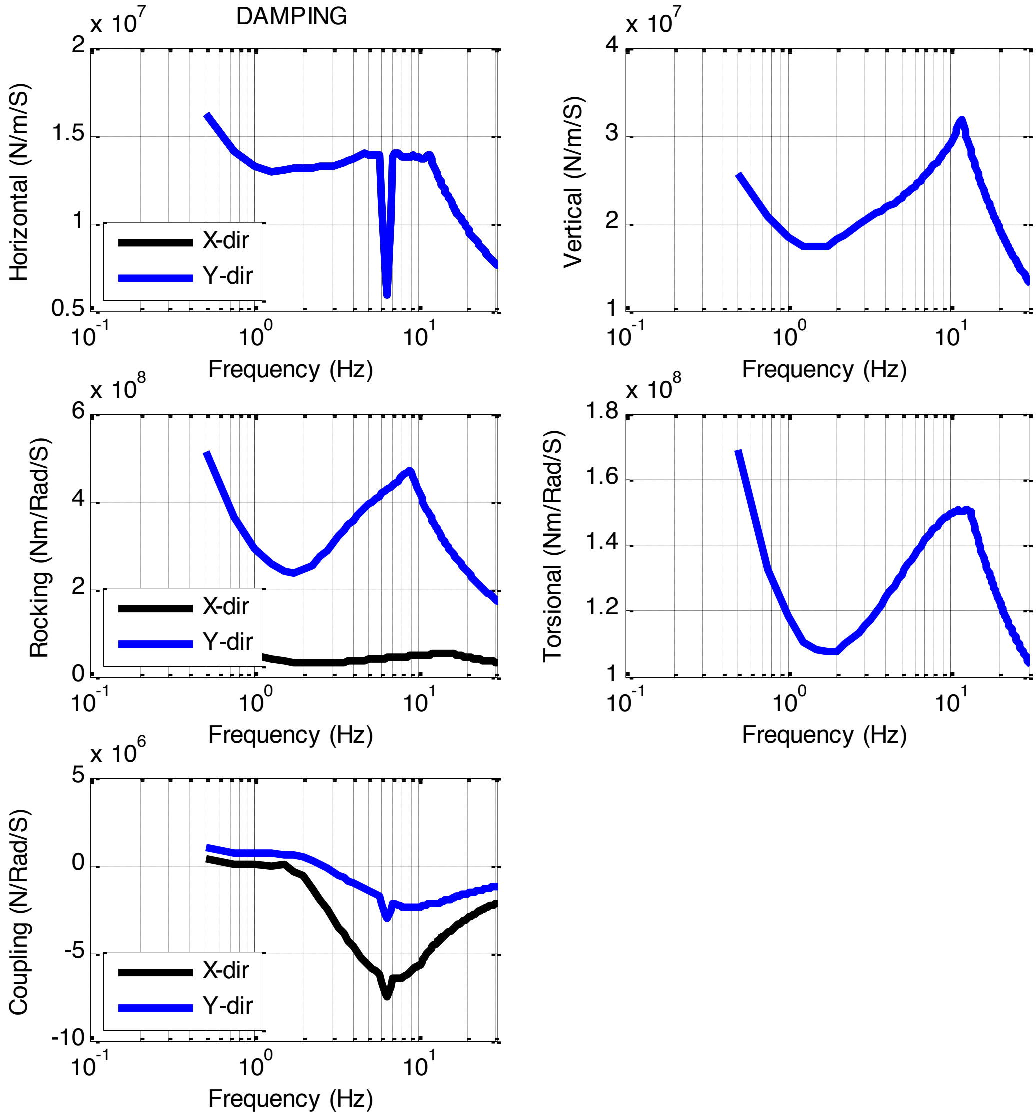


Figure 5.63: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean V_S profile with scaling factor SF3: DAMPING

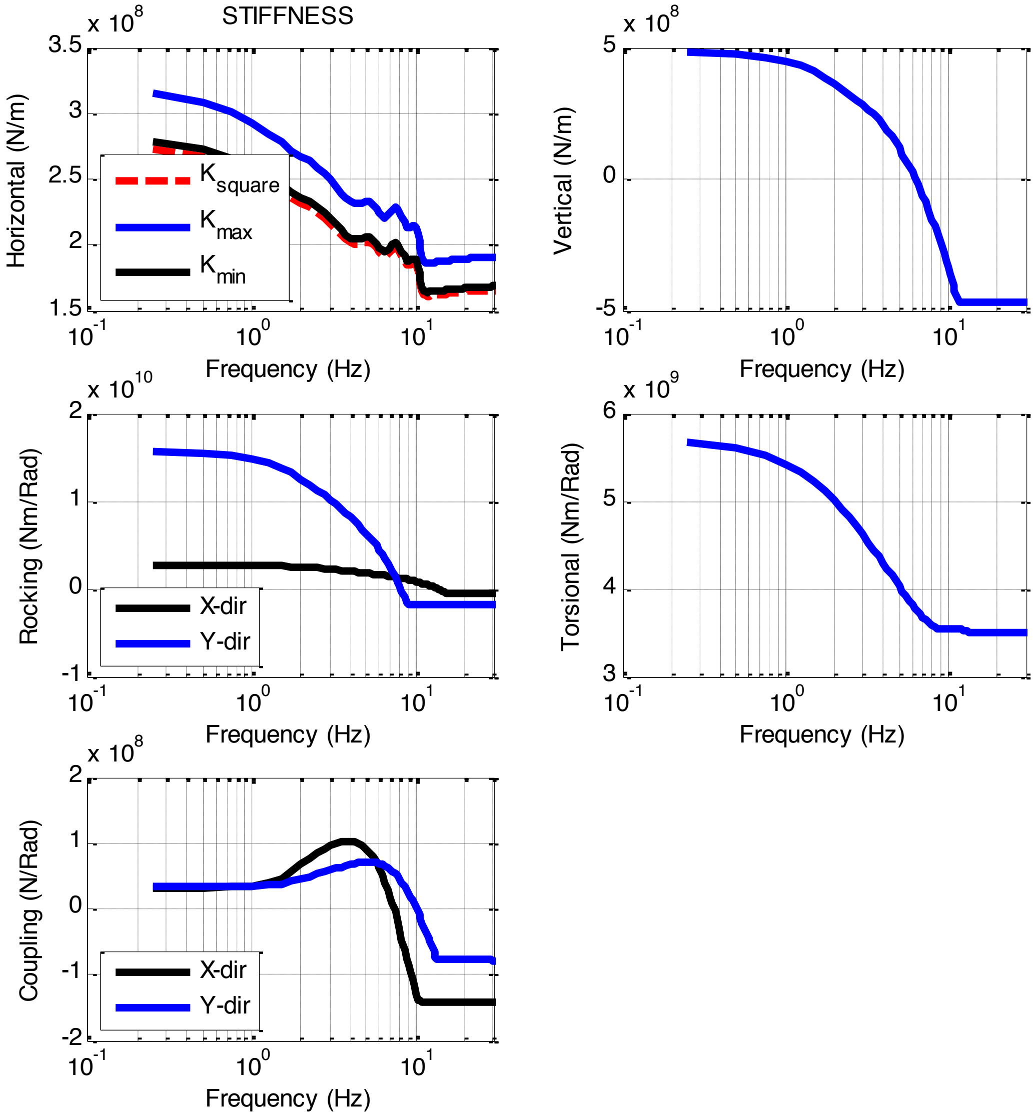


Figure 5.64: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

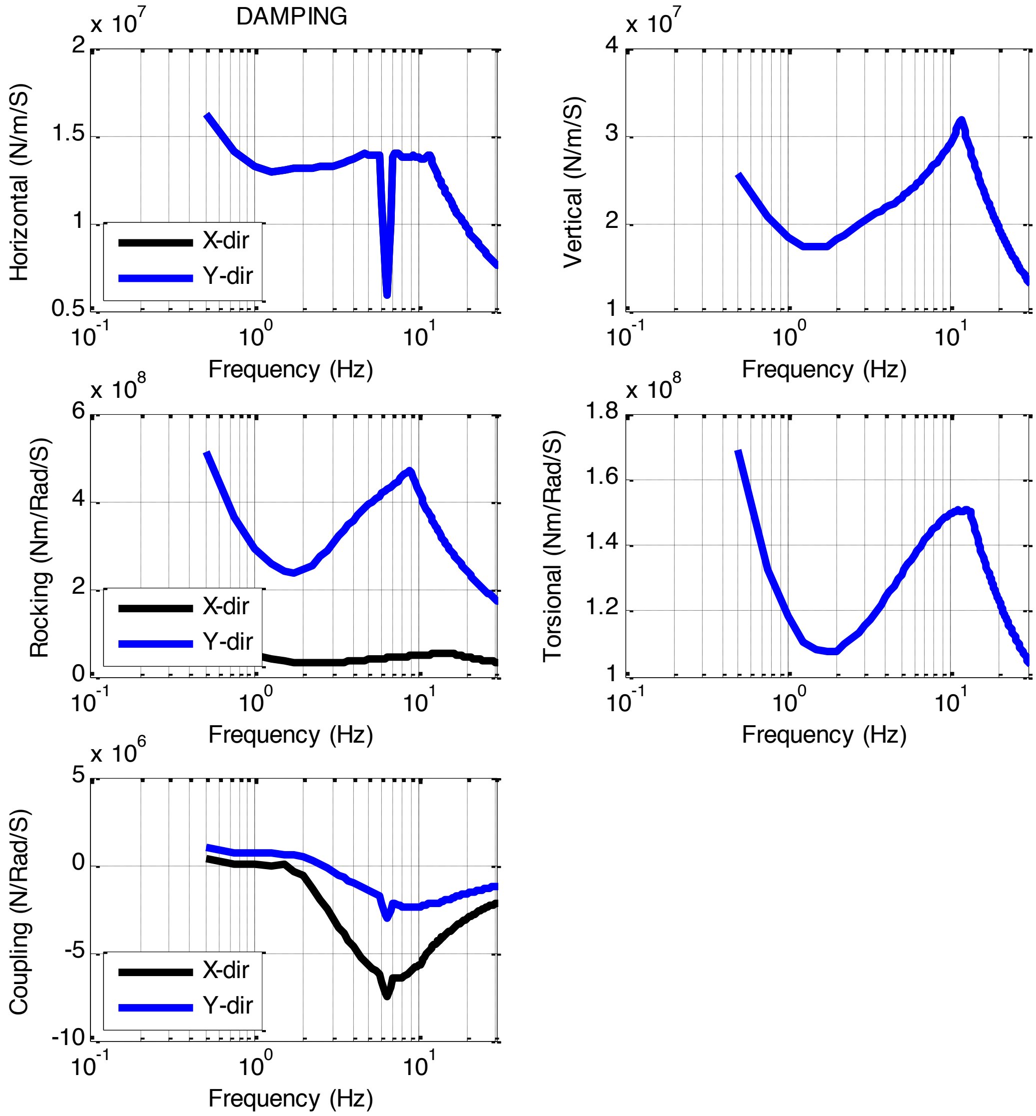


Figure 5.65: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

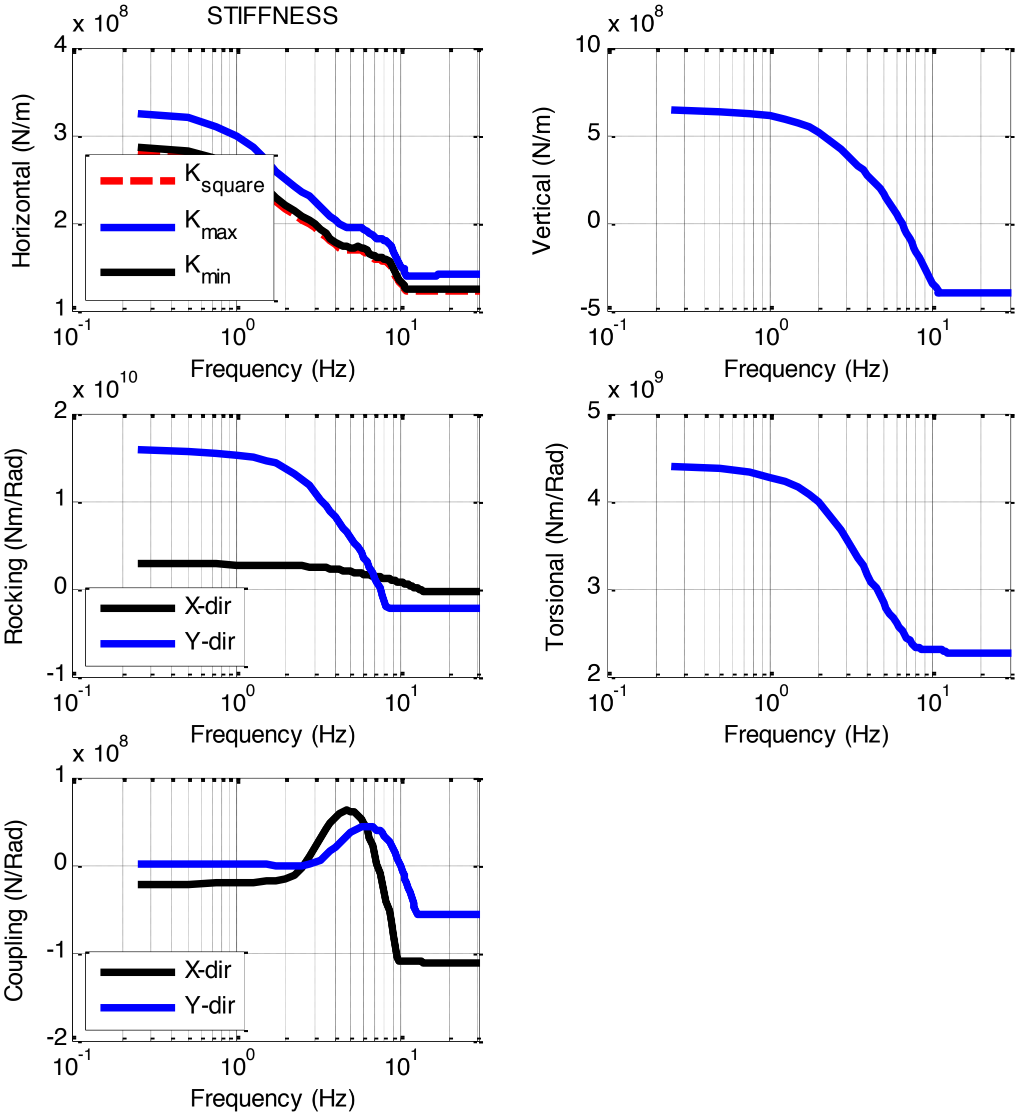


Figure 5.66: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

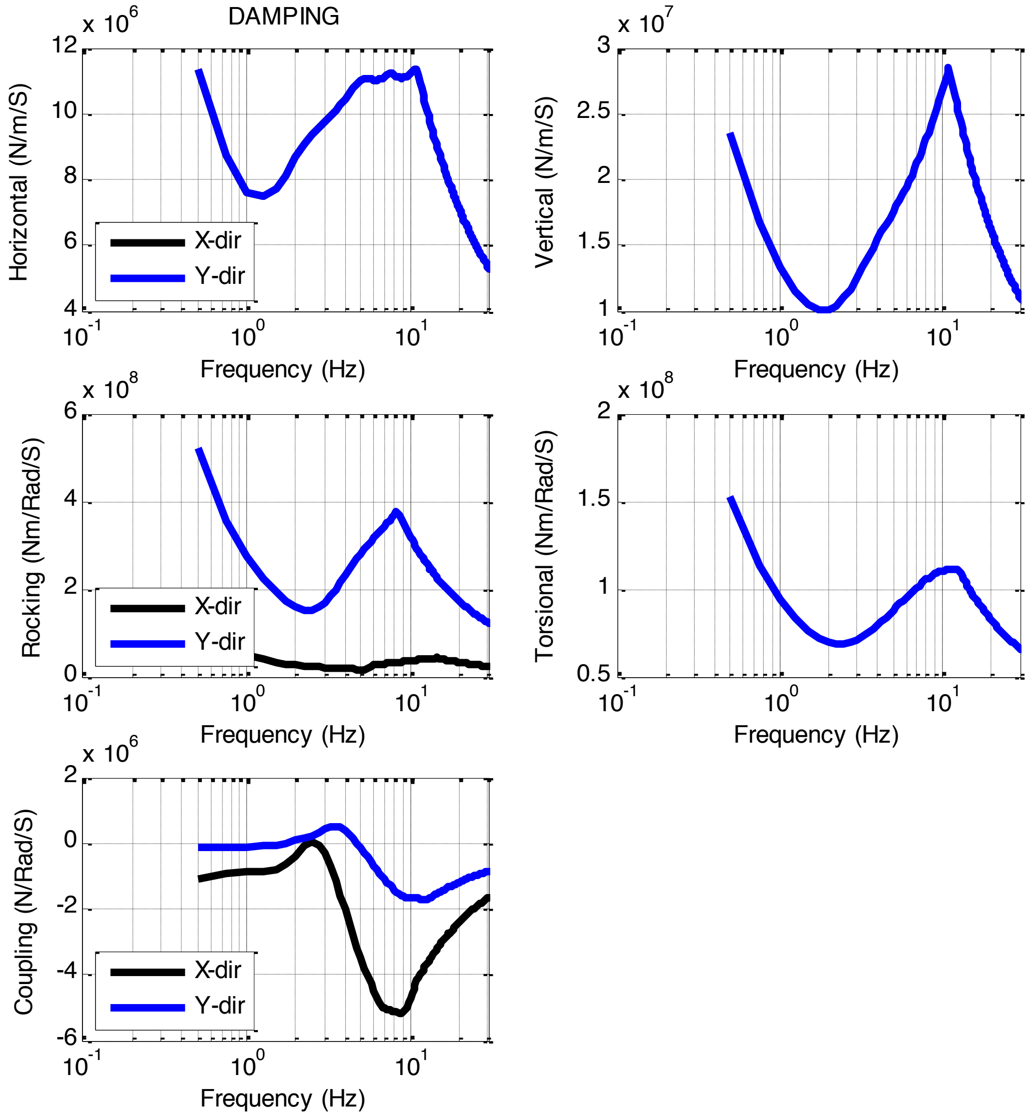


Figure 5.67: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

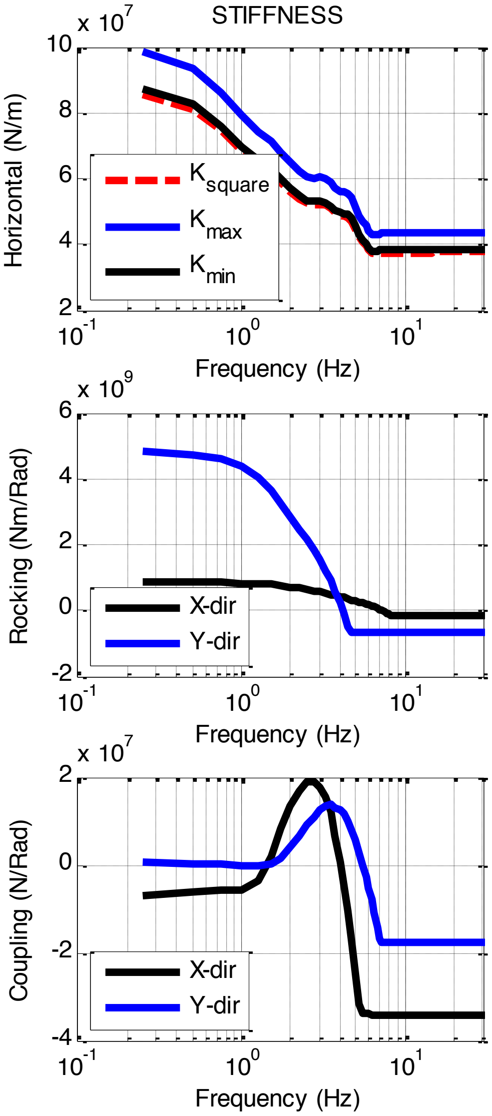


Figure 5.68: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean – standard deviation Vs profile with scaling factor SF3: STIFFNESS

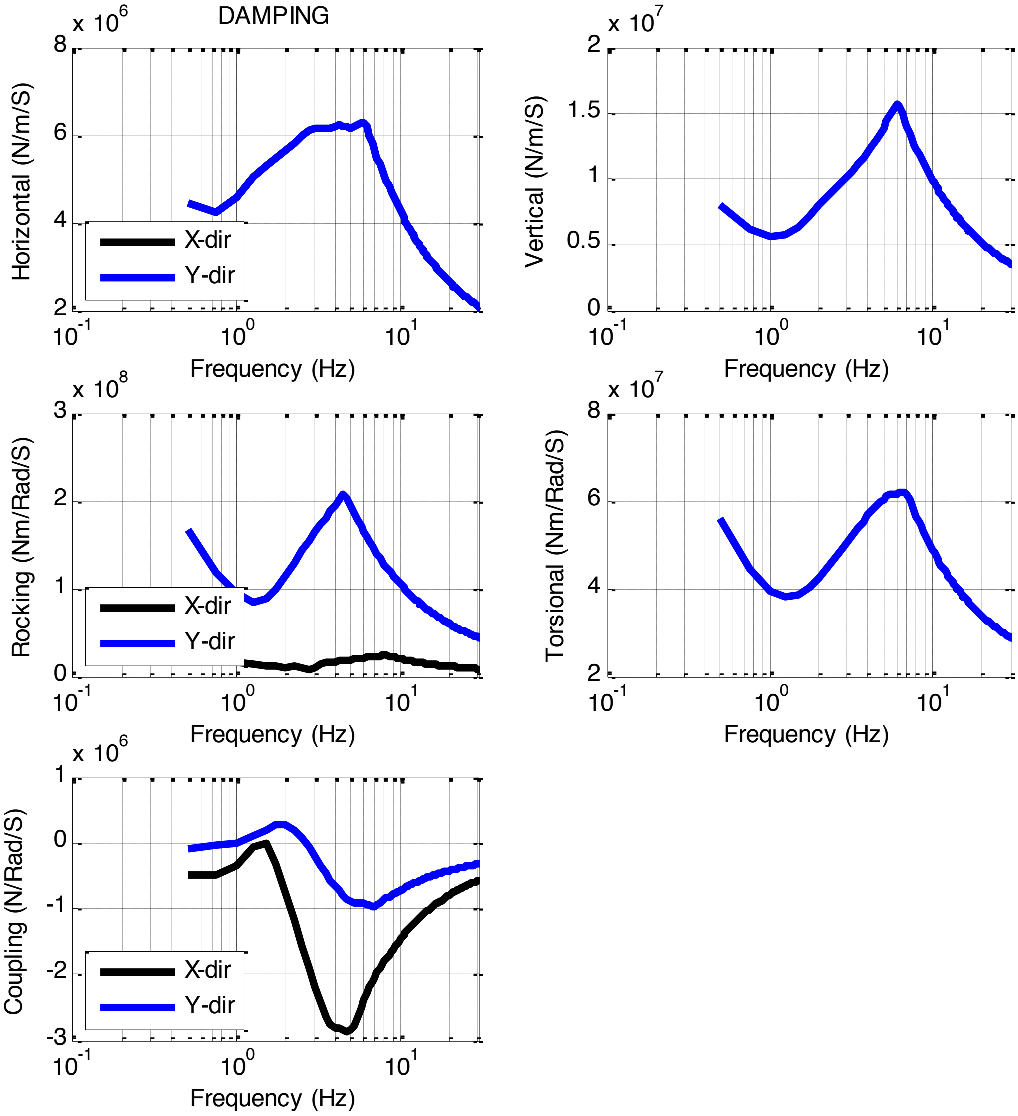


Figure 5.69: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

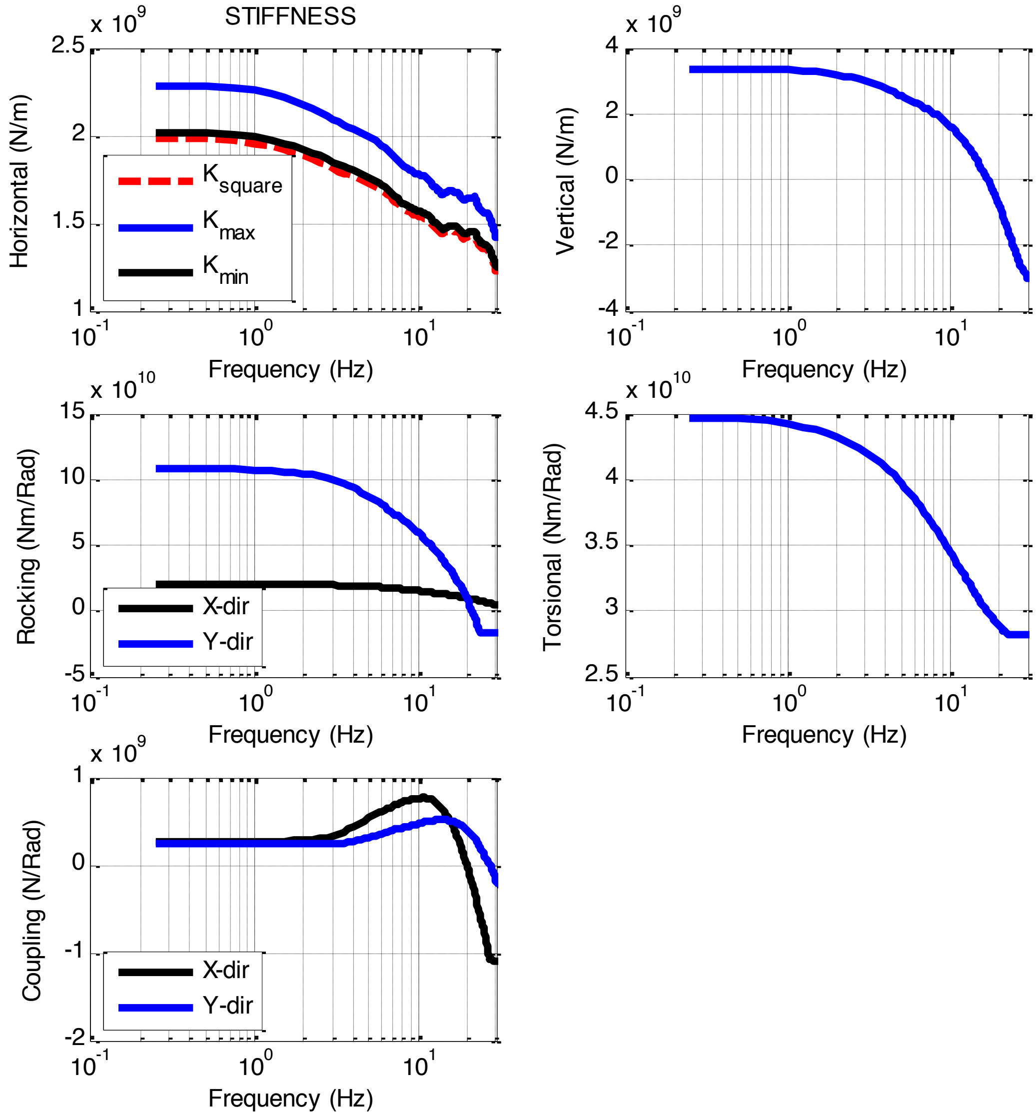


Figure 5.70: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

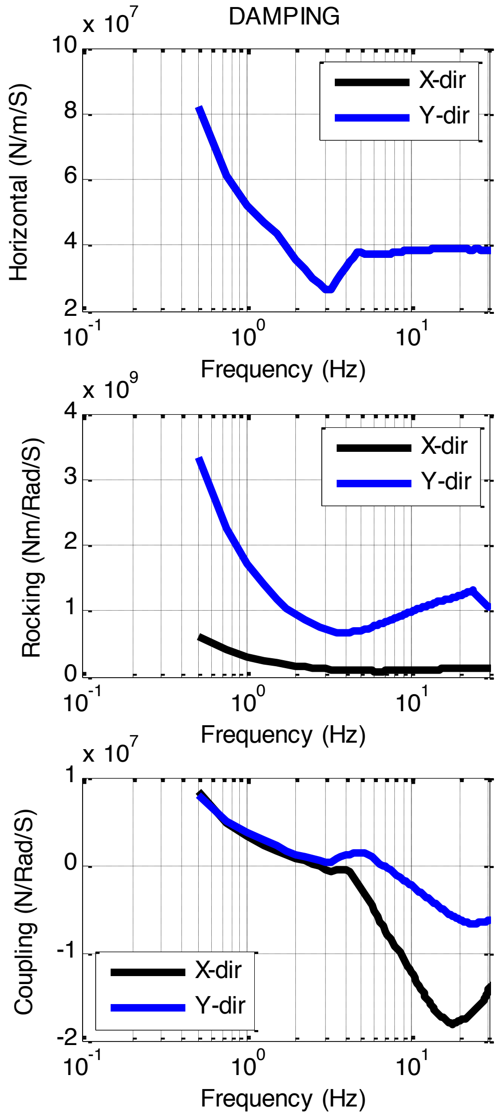


Figure 5.71: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

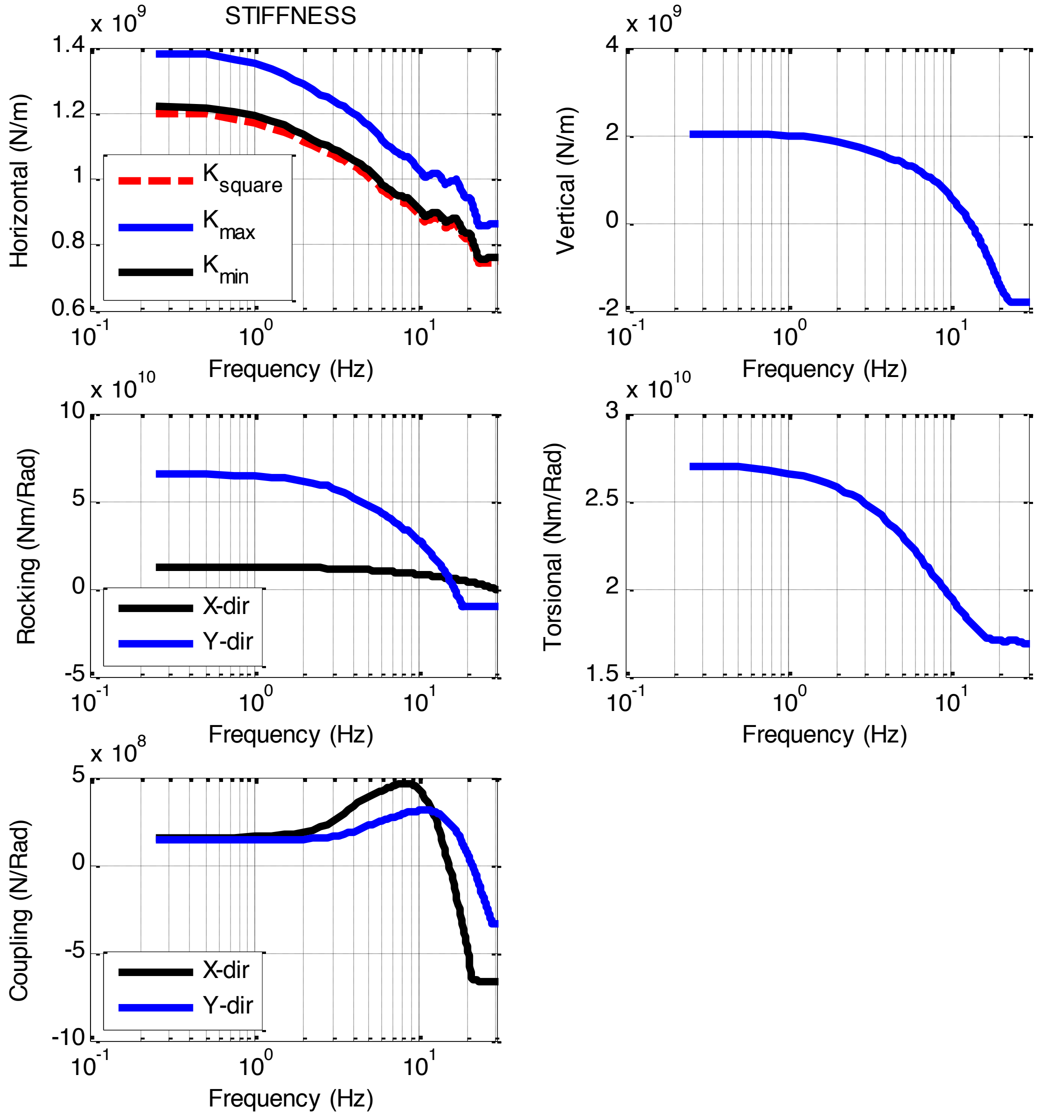


Figure 5.72: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

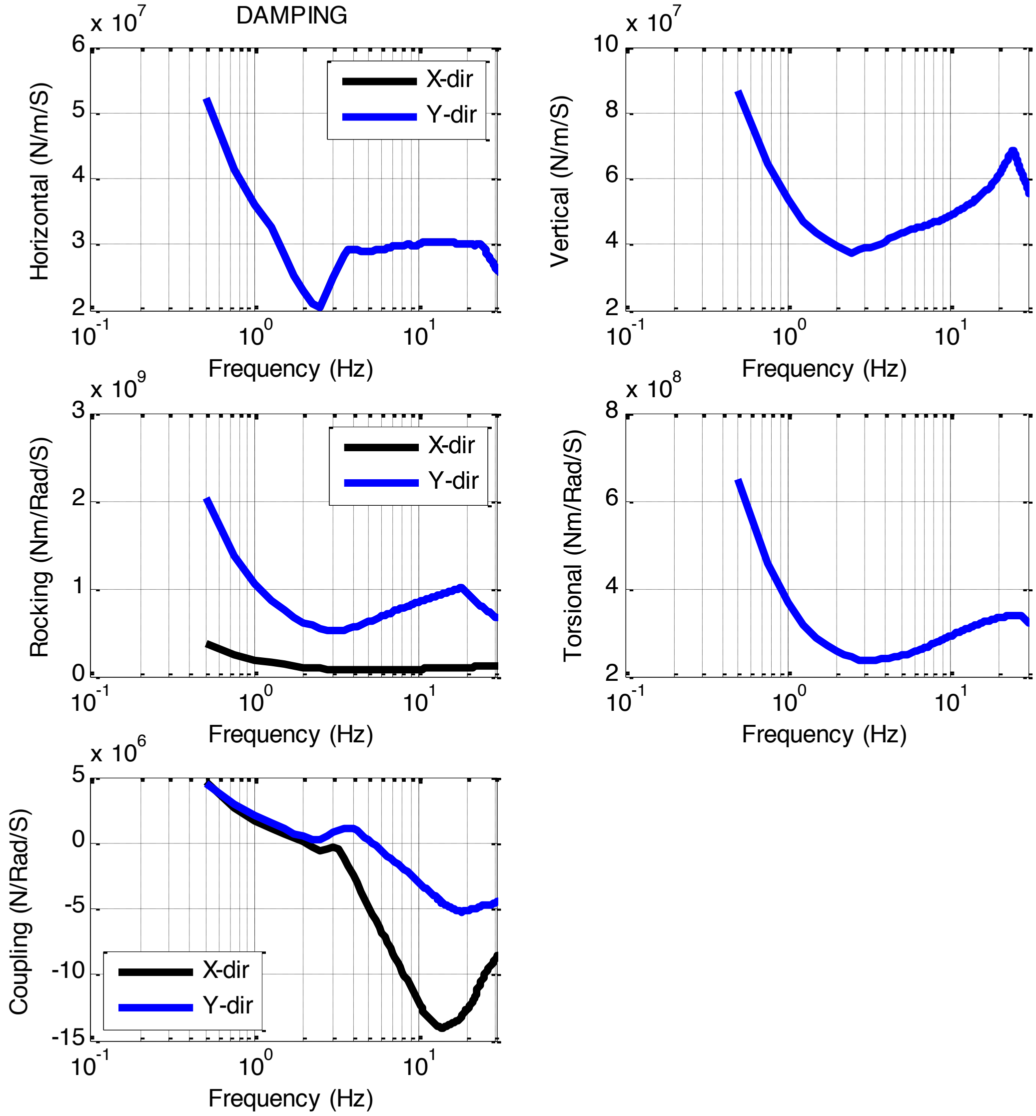


Figure 5.73: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

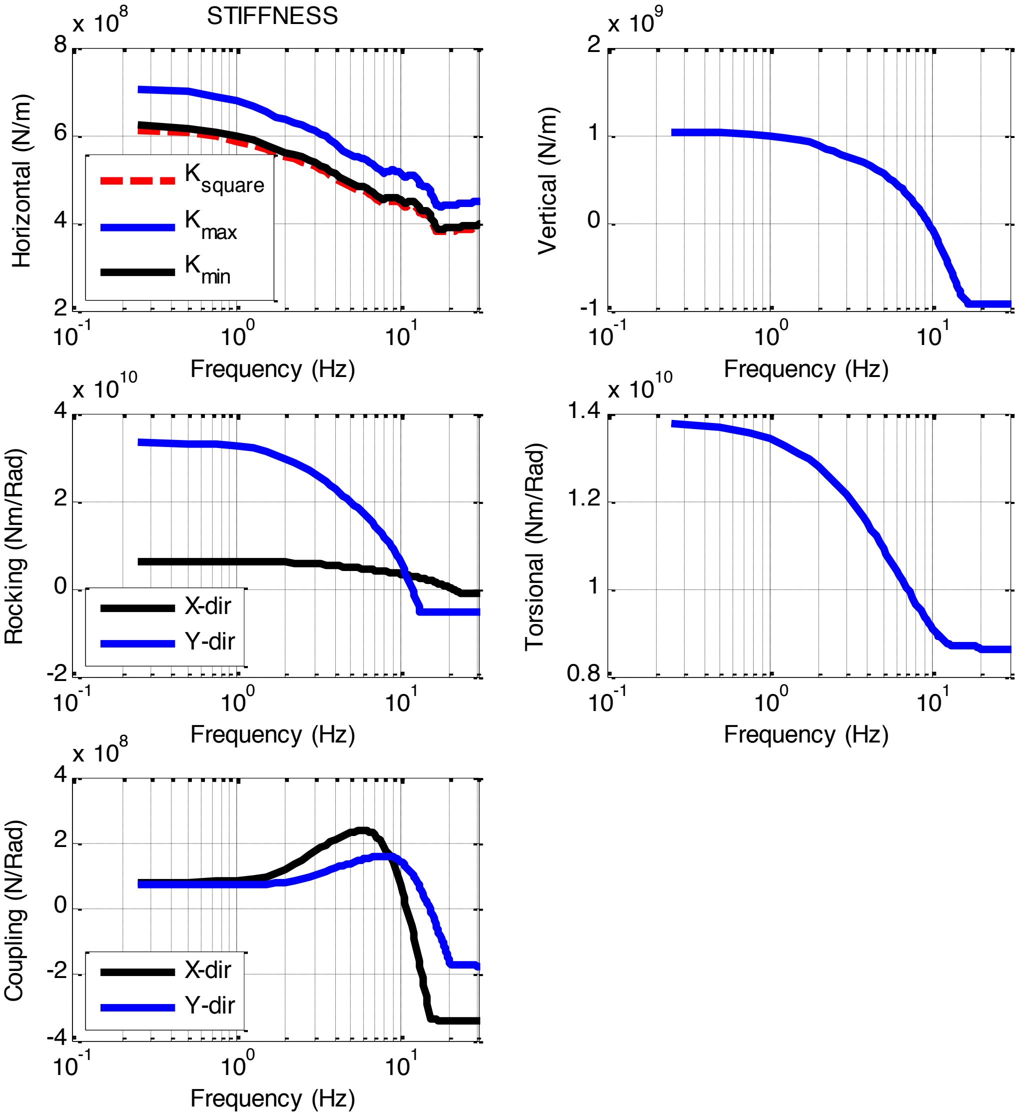


Figure 5.74: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

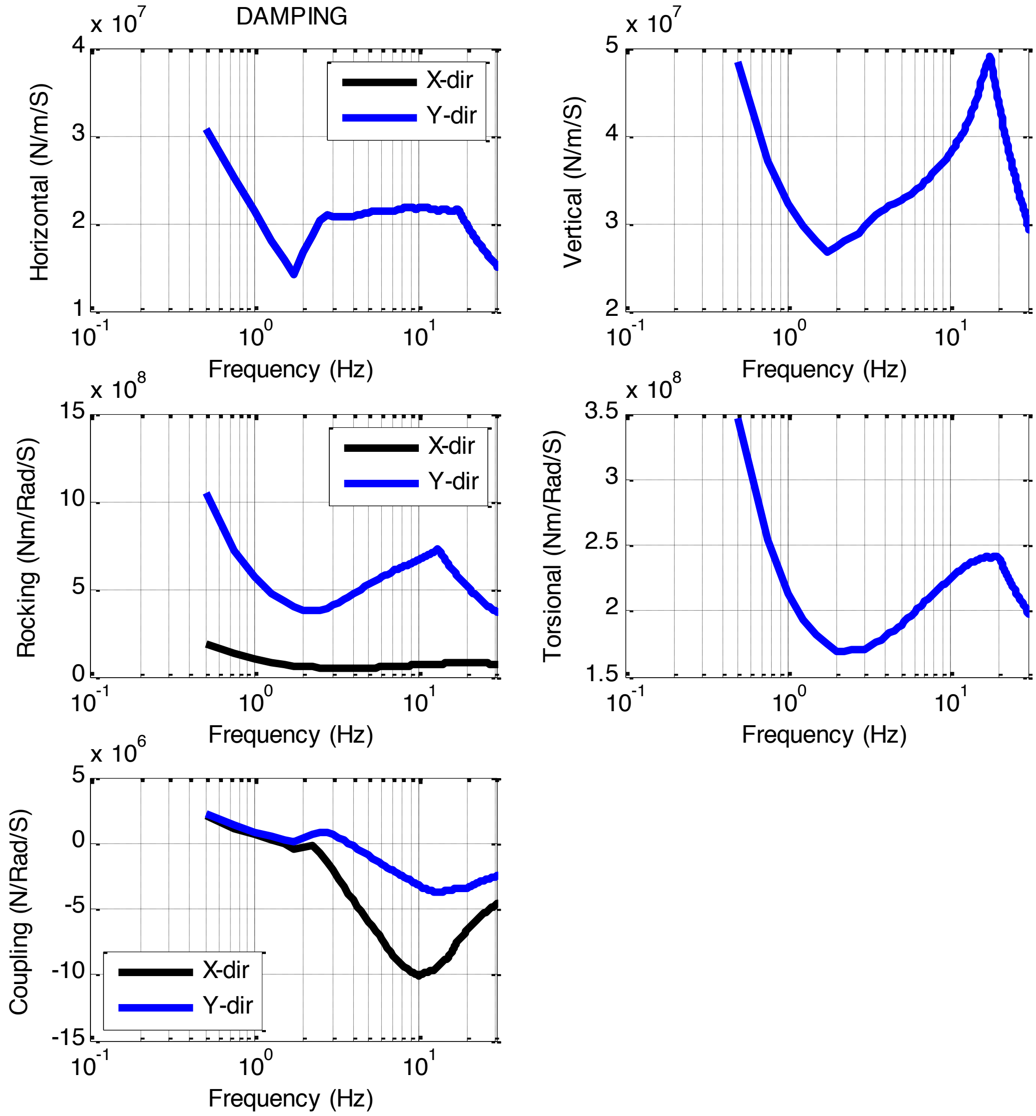


Figure 5.75: Terraced Building with 4 Units on shallow foundations - Masonry foundations – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

5.3.2 Concrete foundations

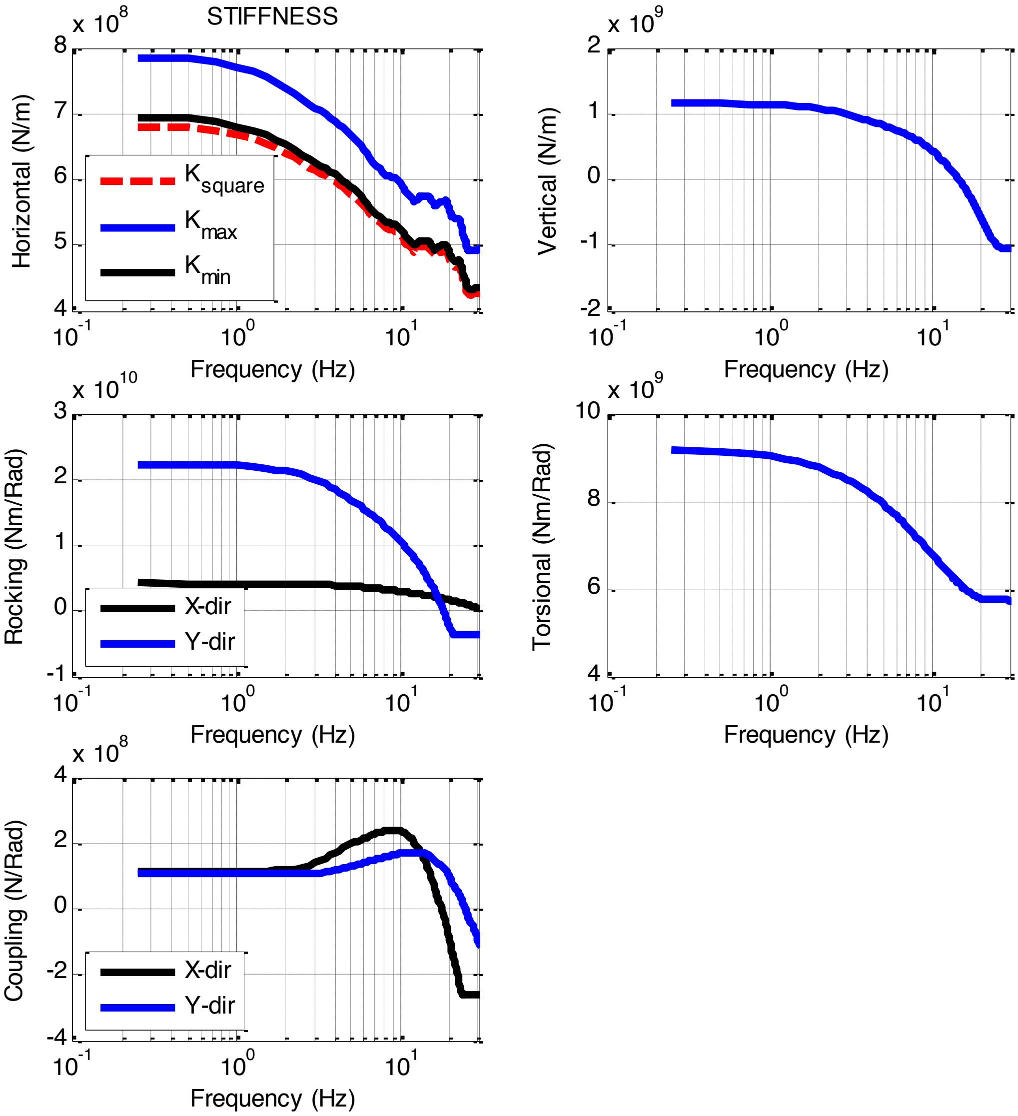


Figure 5.76: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: STIFFNESS

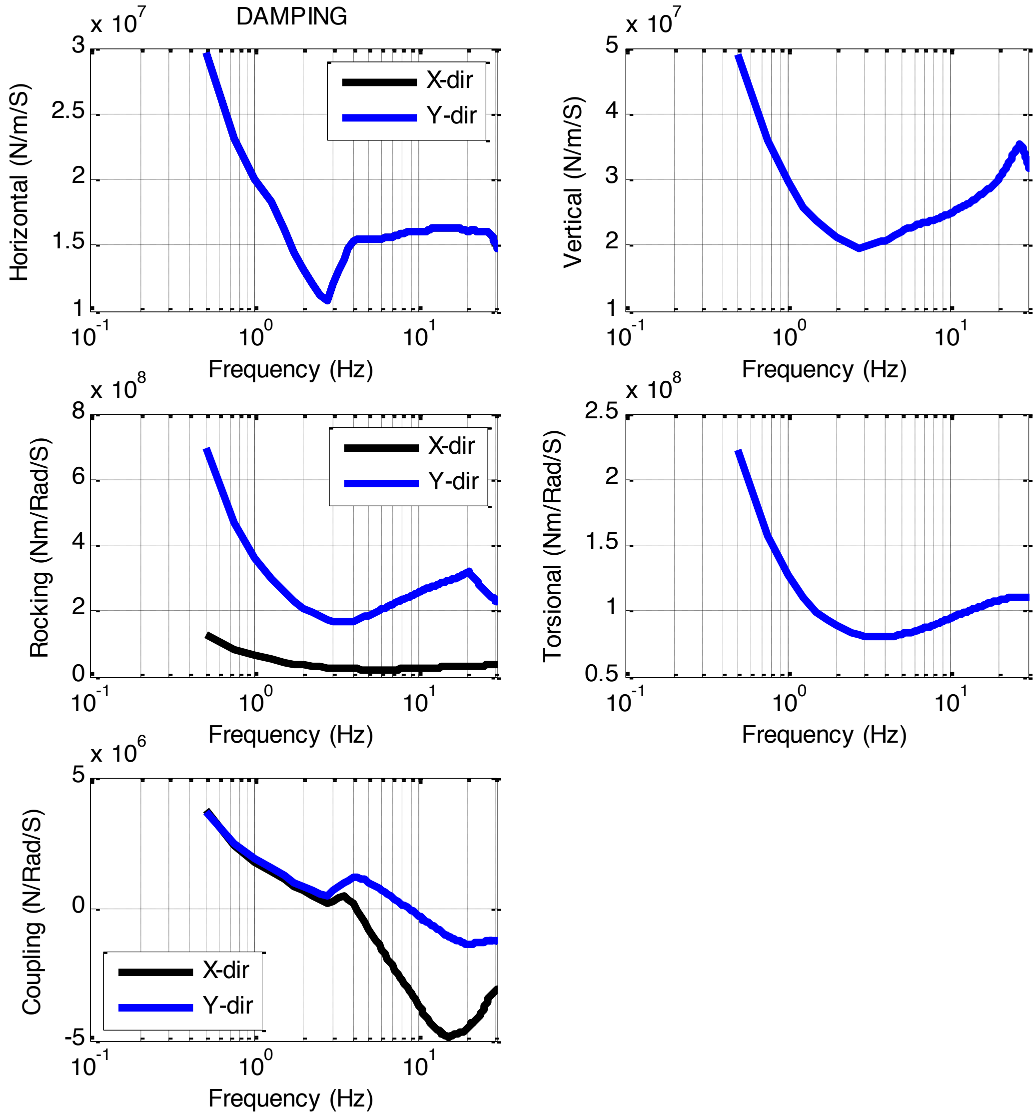


Figure 5.77: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: DAMPING

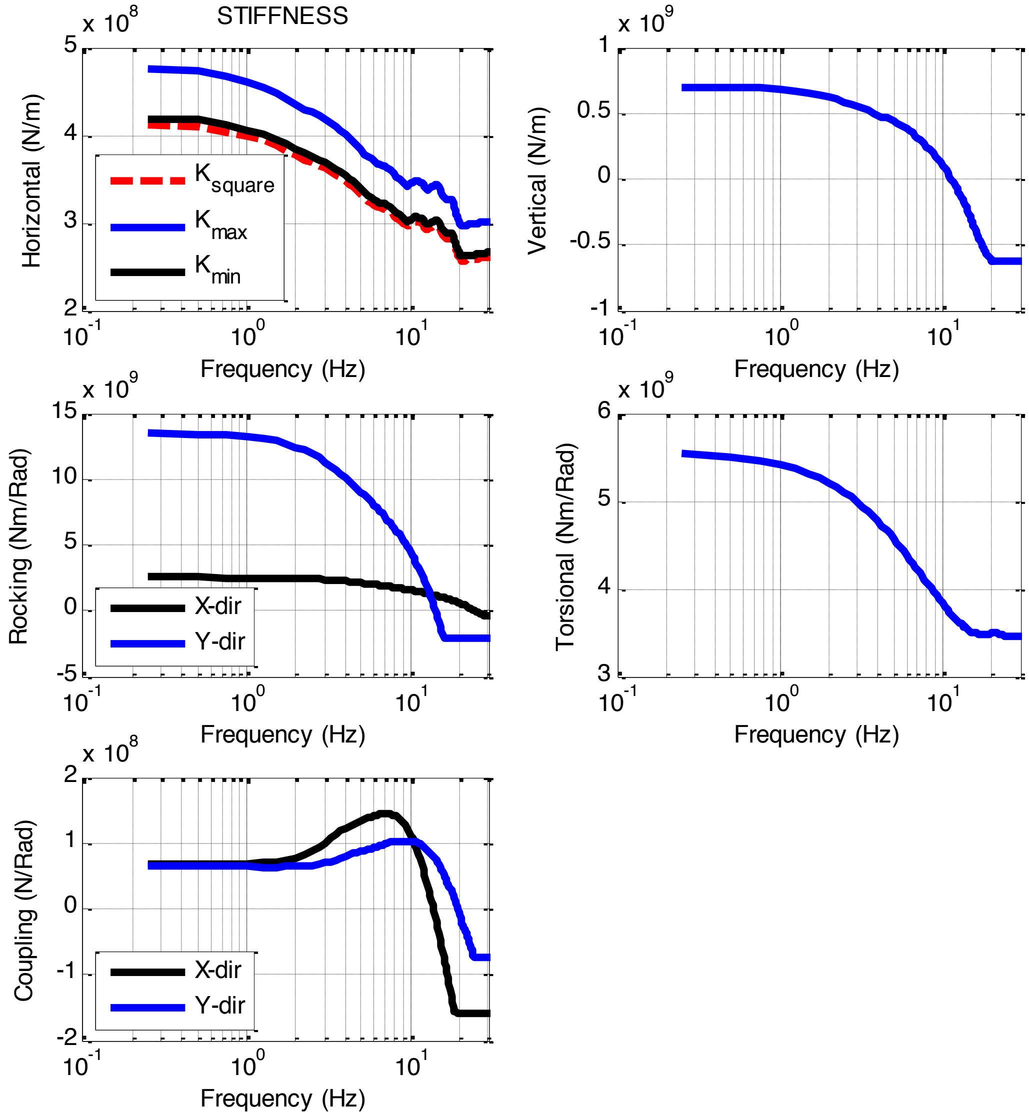


Figure 5.78: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: STIFFNESS

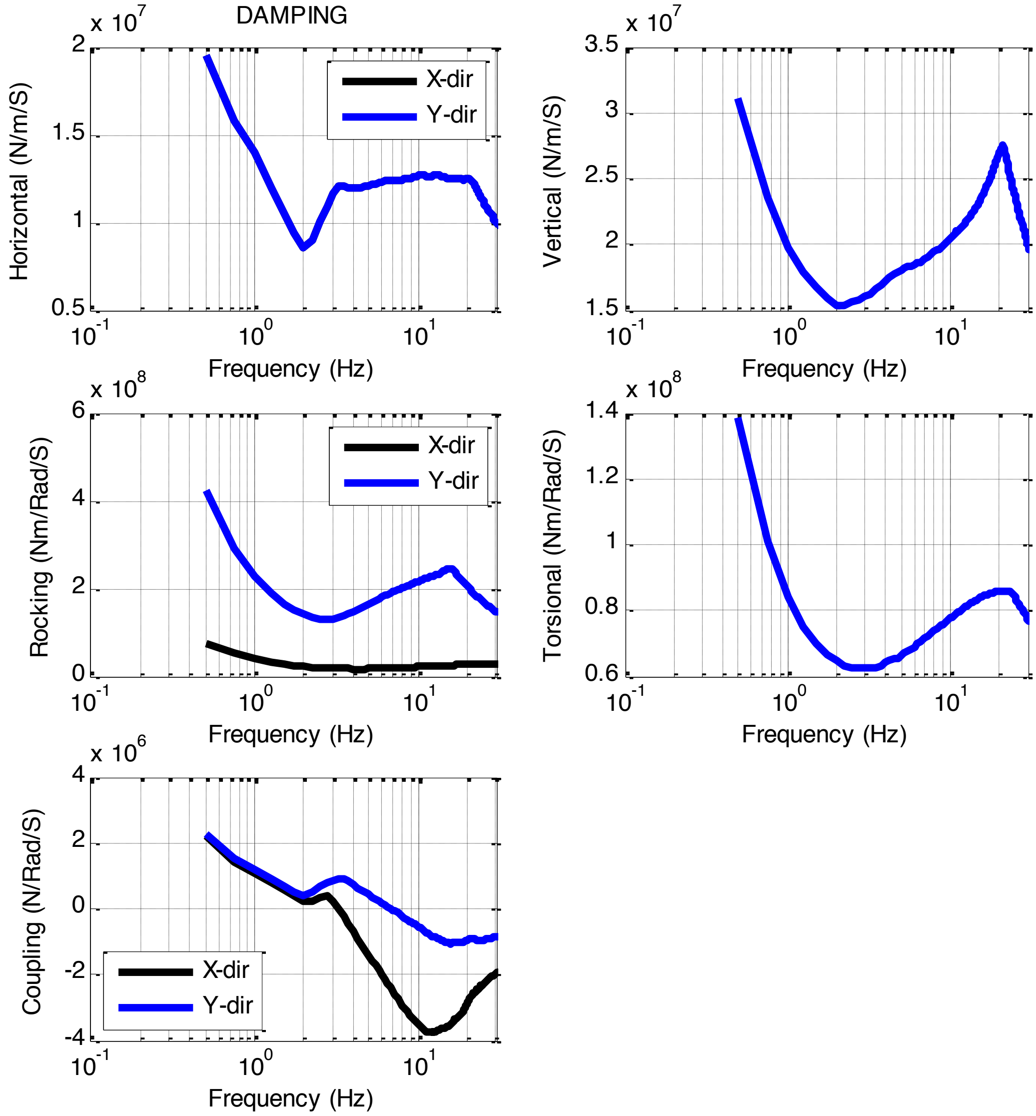


Figure 5.79: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: DAMPING

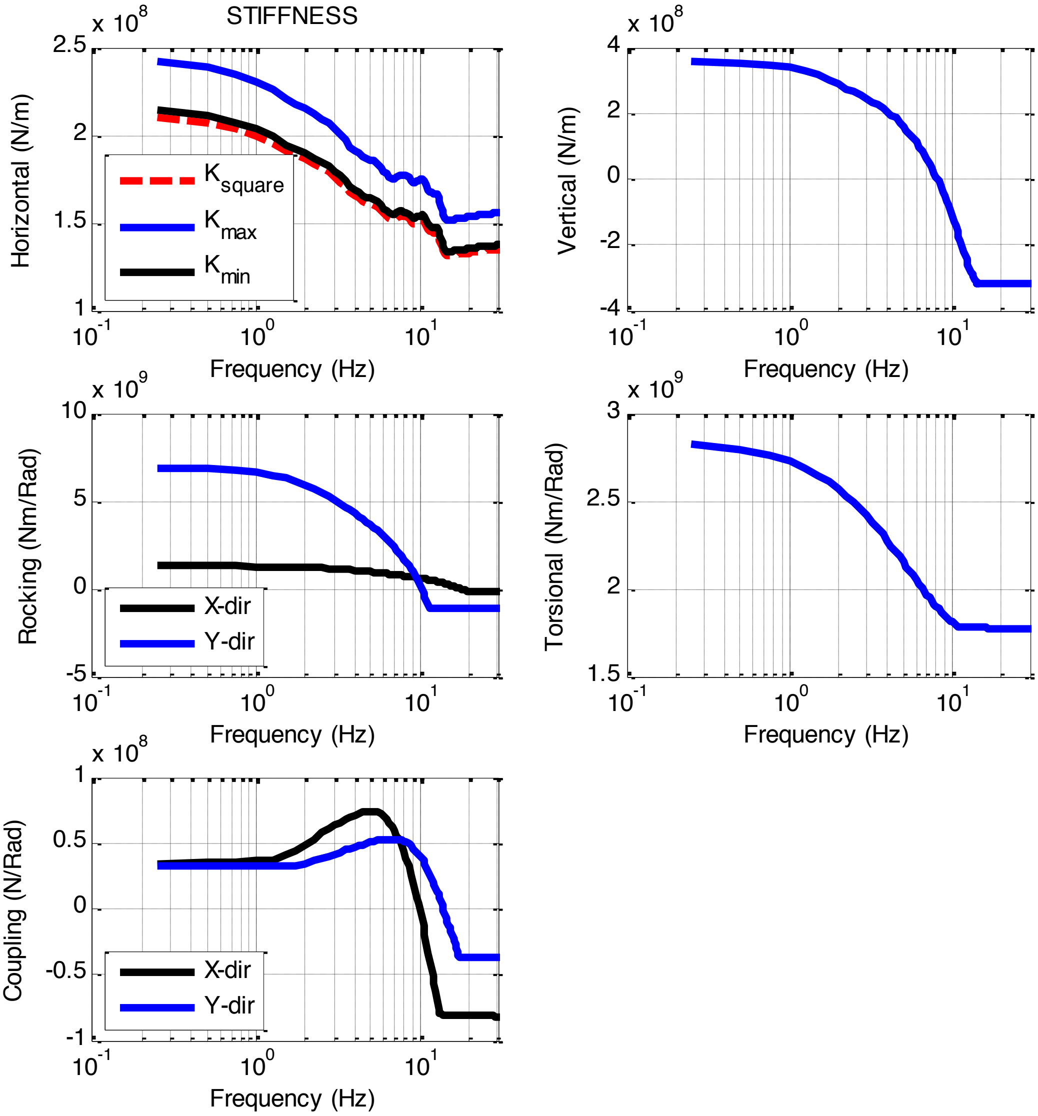


Figure 5.80: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: STIFFNESS

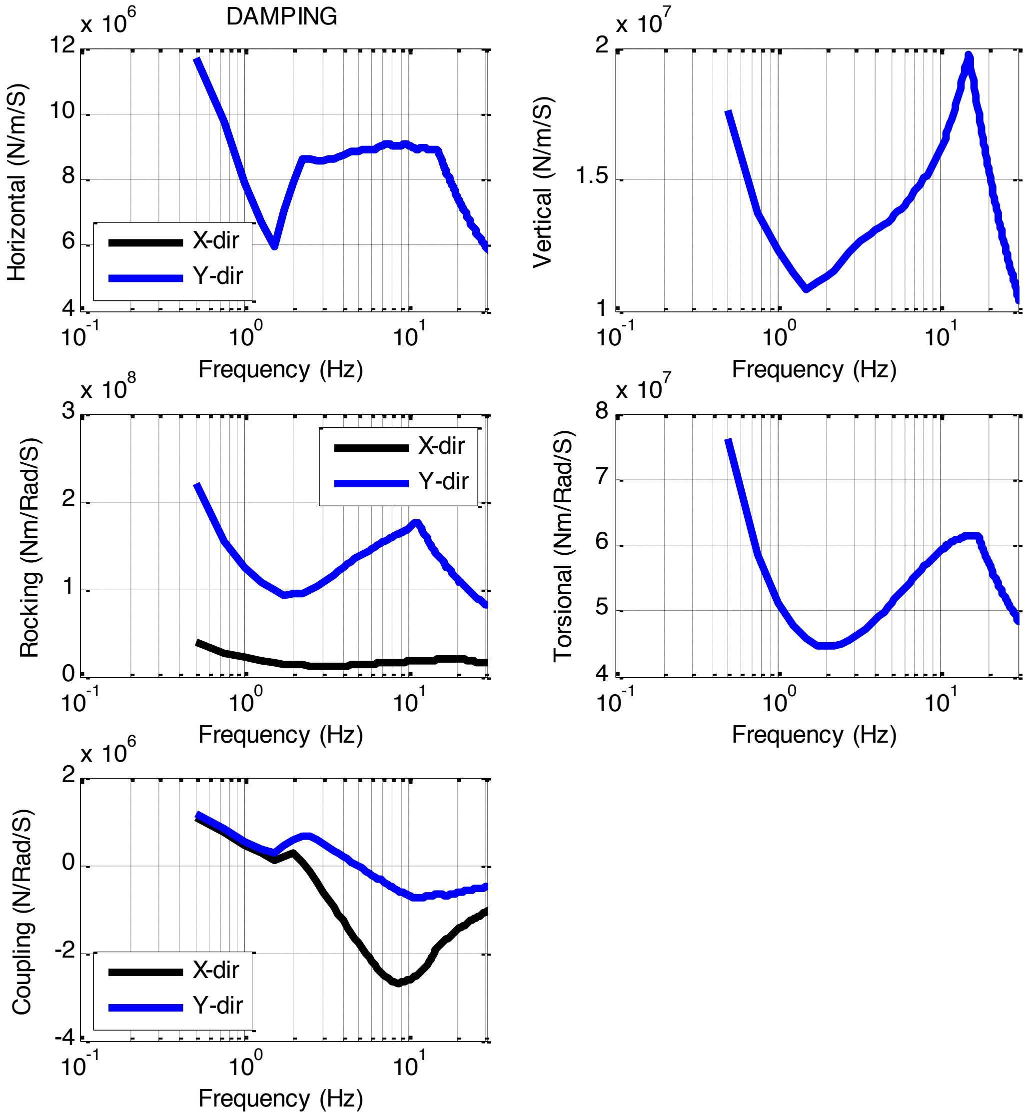


Figure 5.81: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: DAMPING

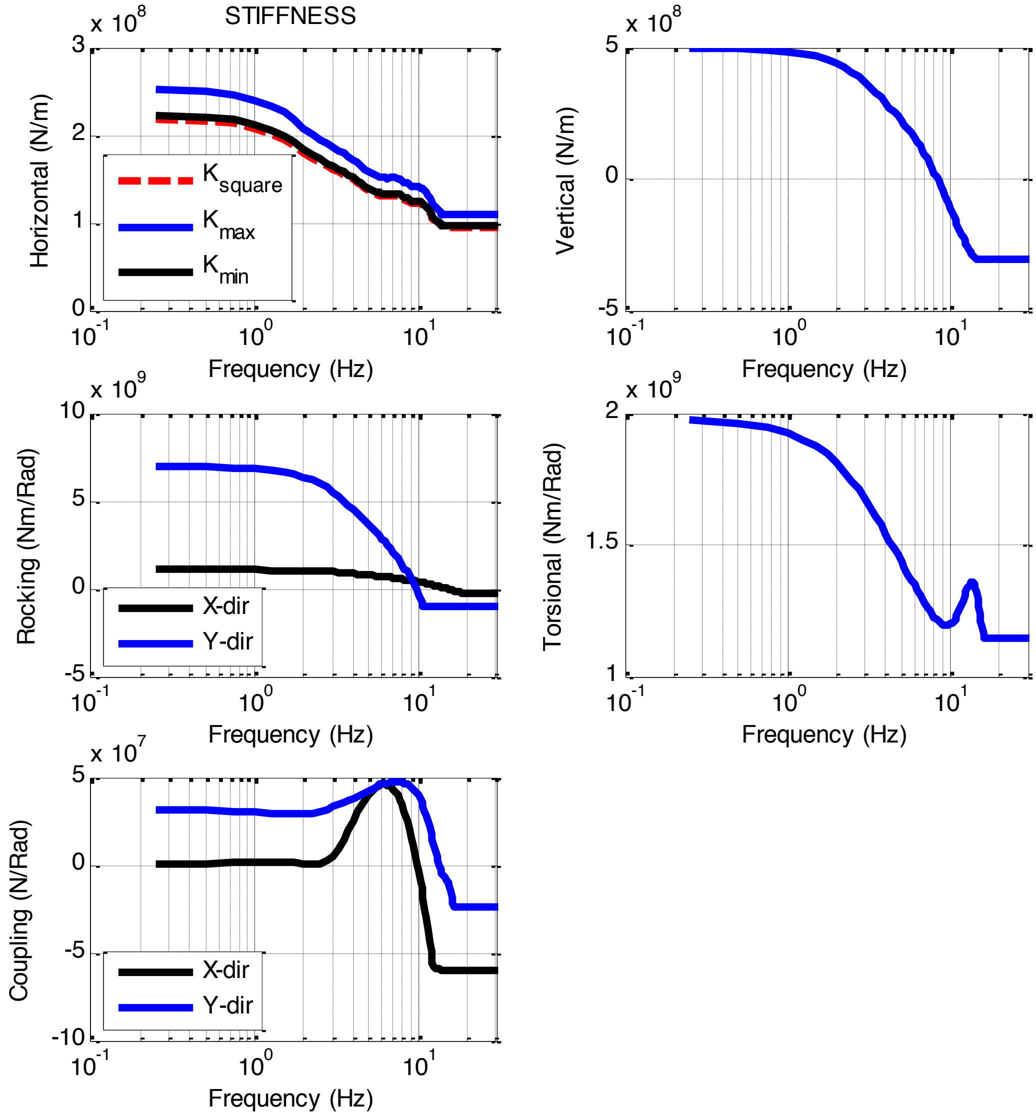


Figure 5.82: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

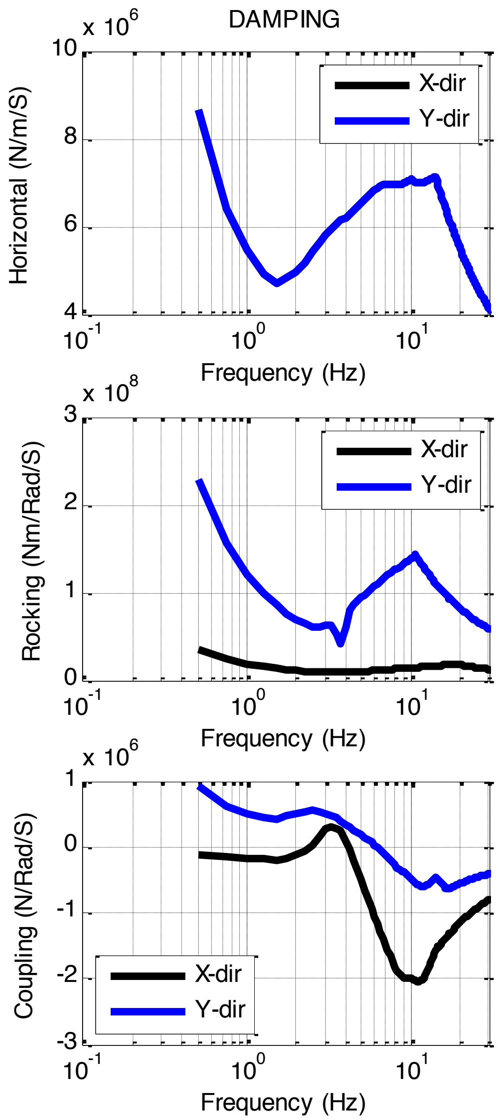


Figure 5.83: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

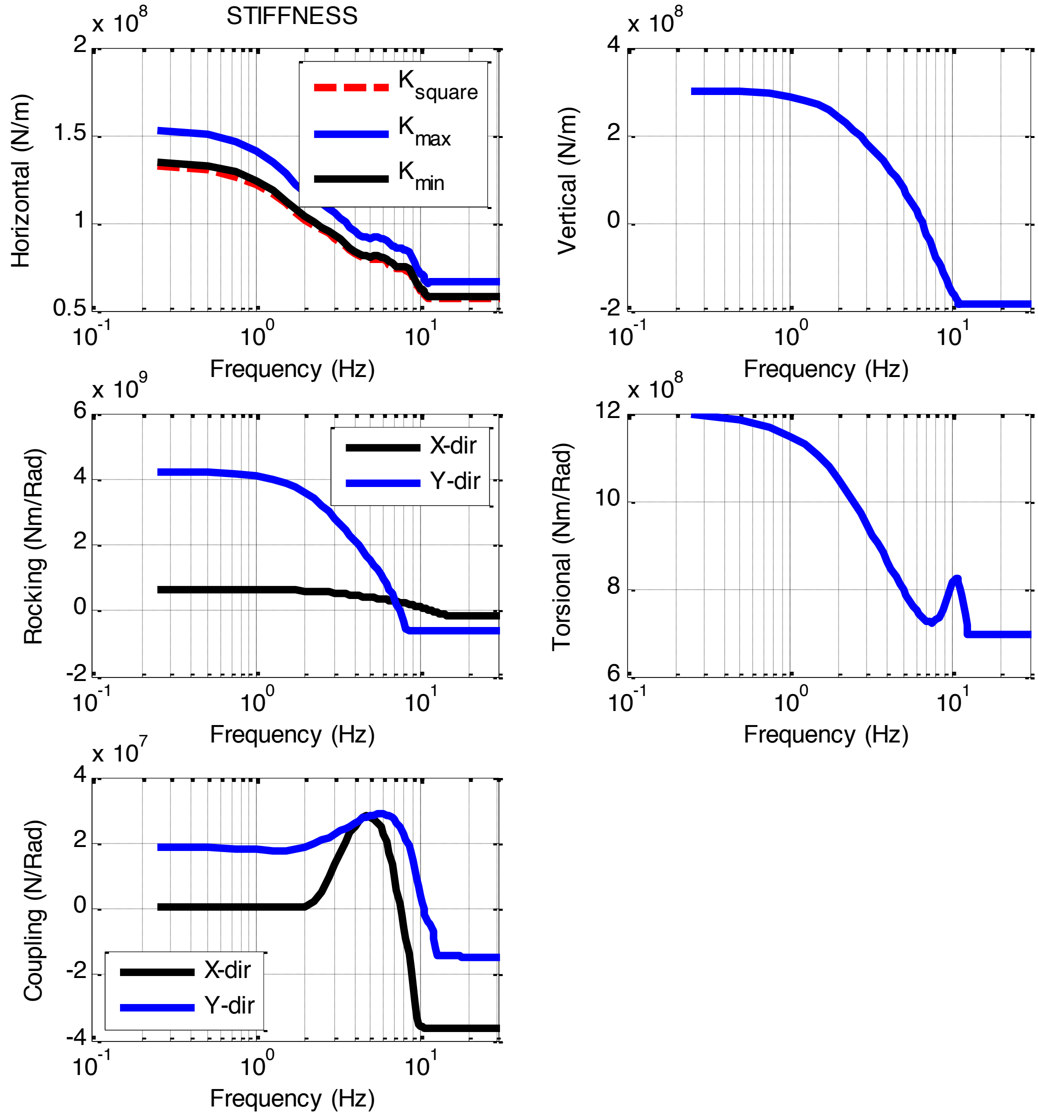


Figure 5.84: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

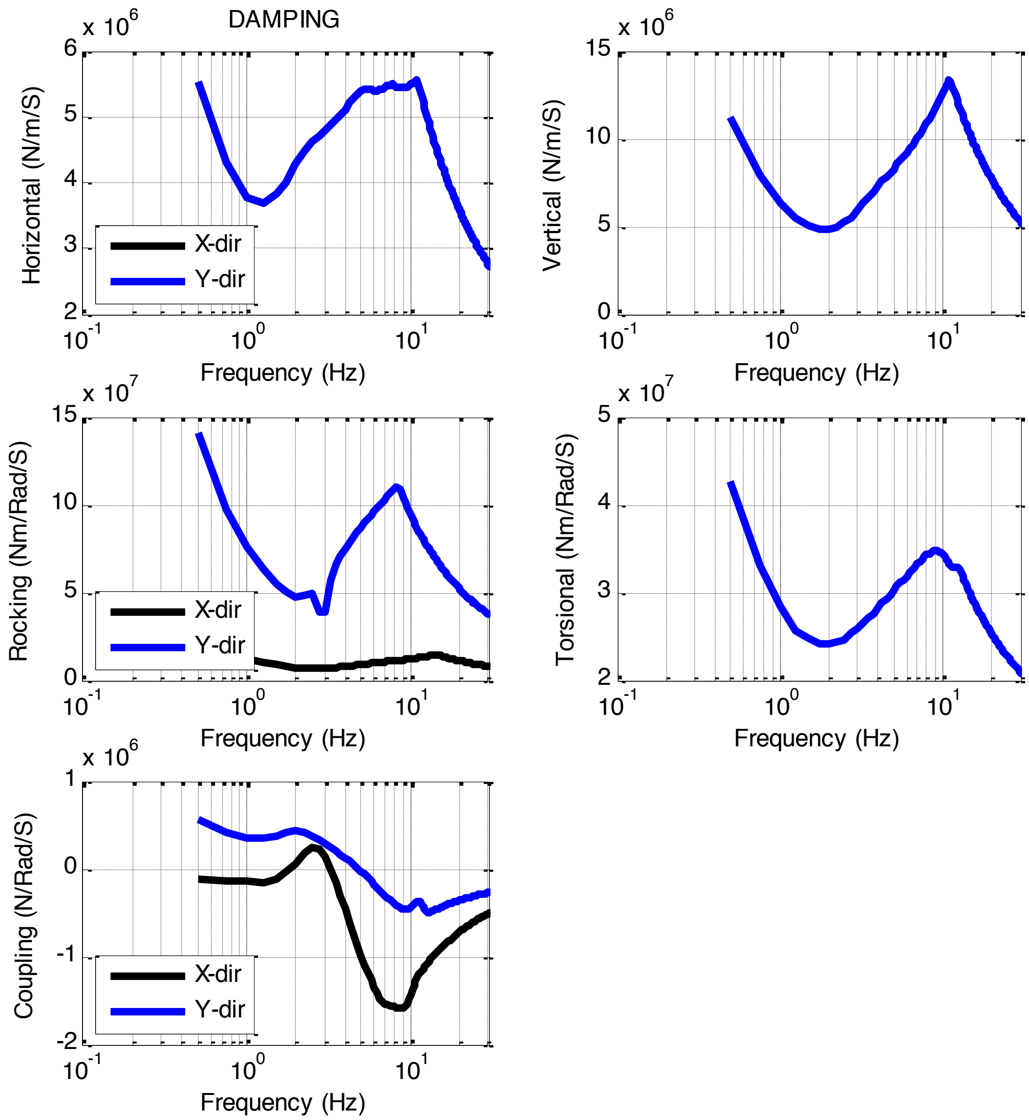


Figure 5.85: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

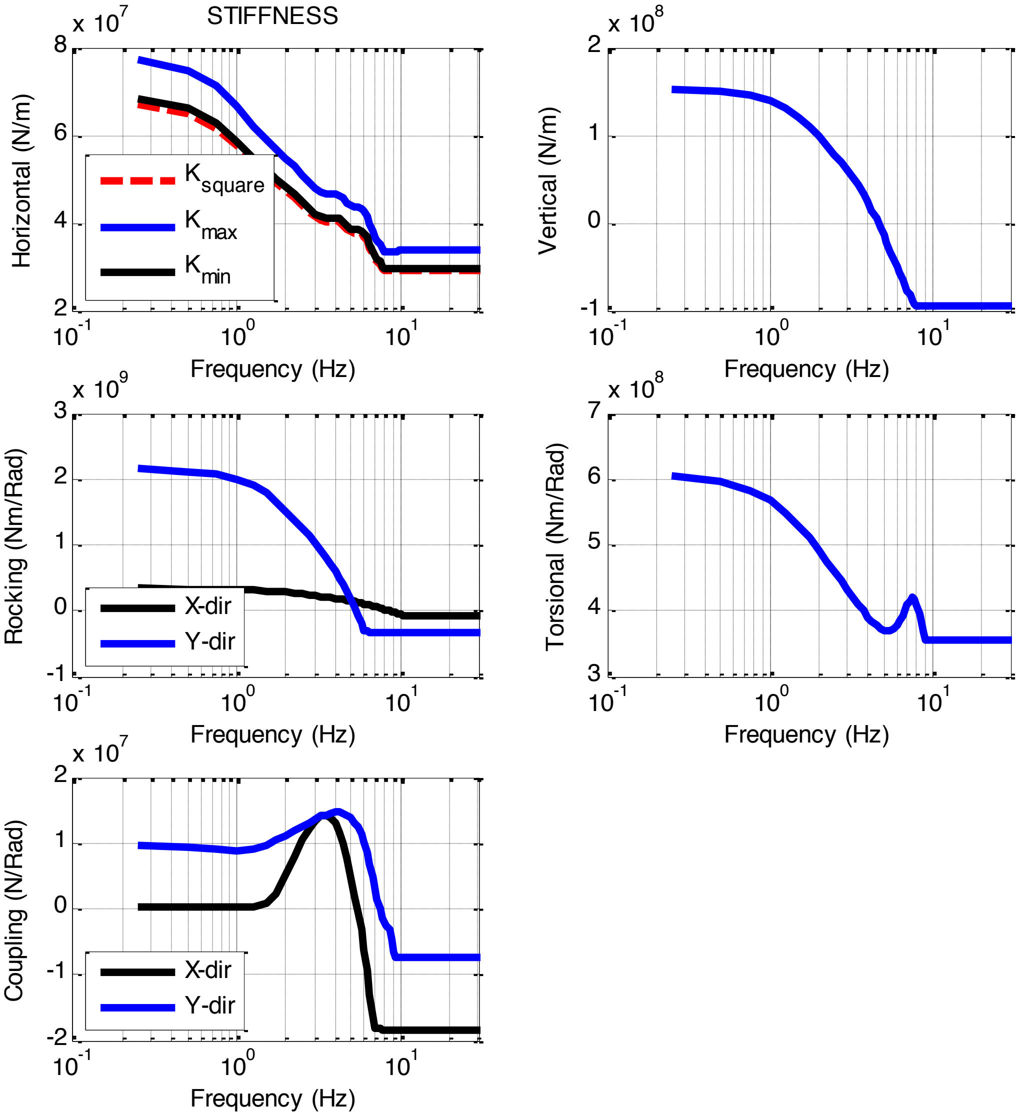


Figure 5.86: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

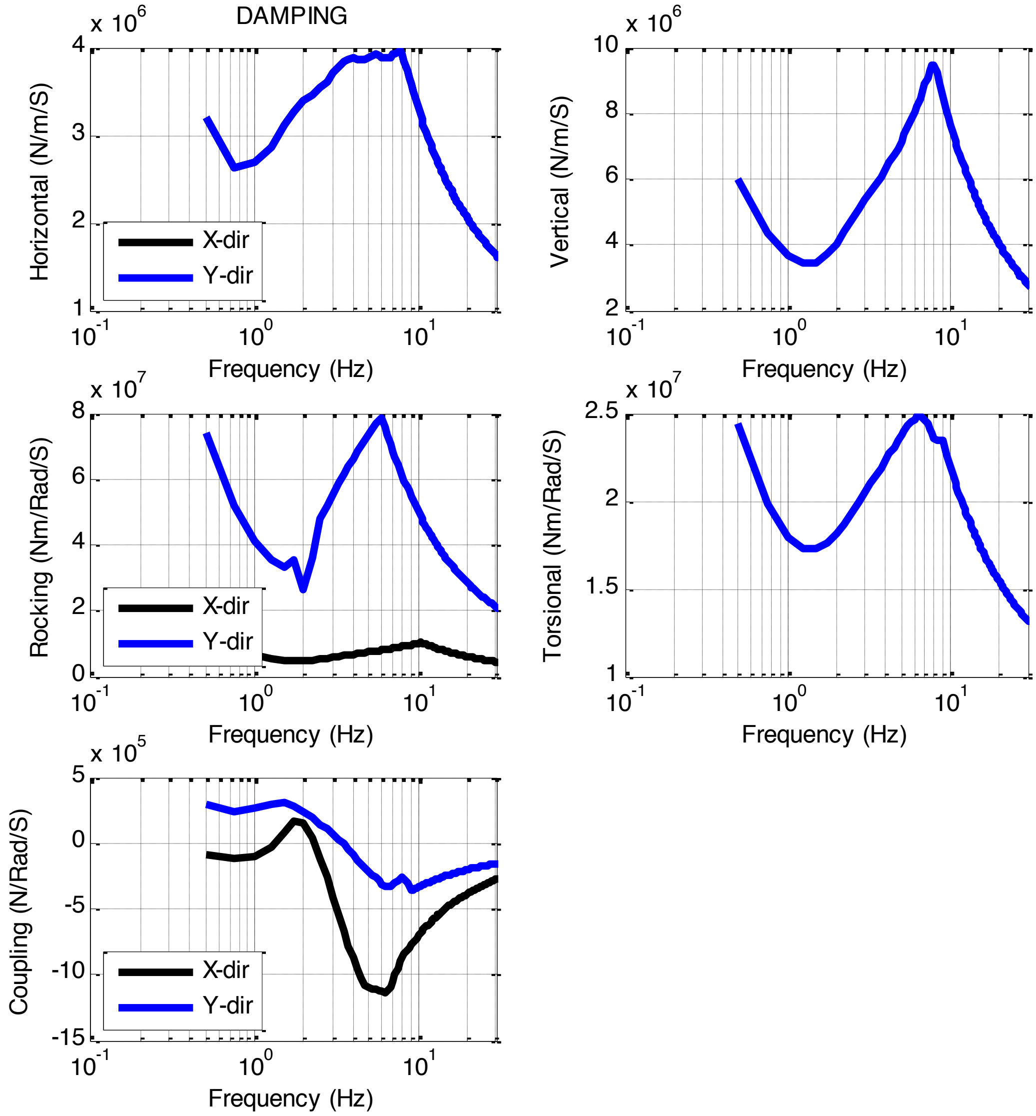


Figure 5.87: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

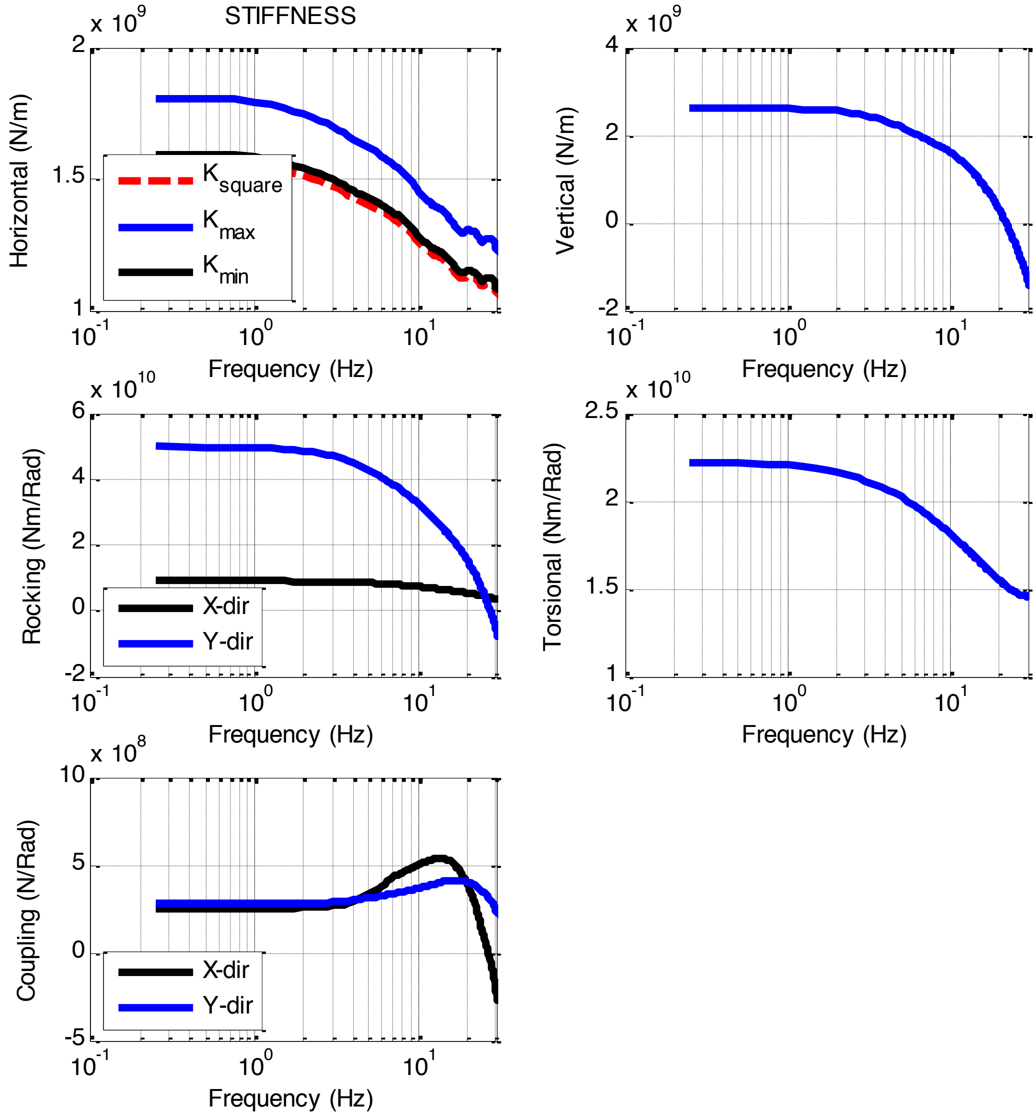


Figure 5.88: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

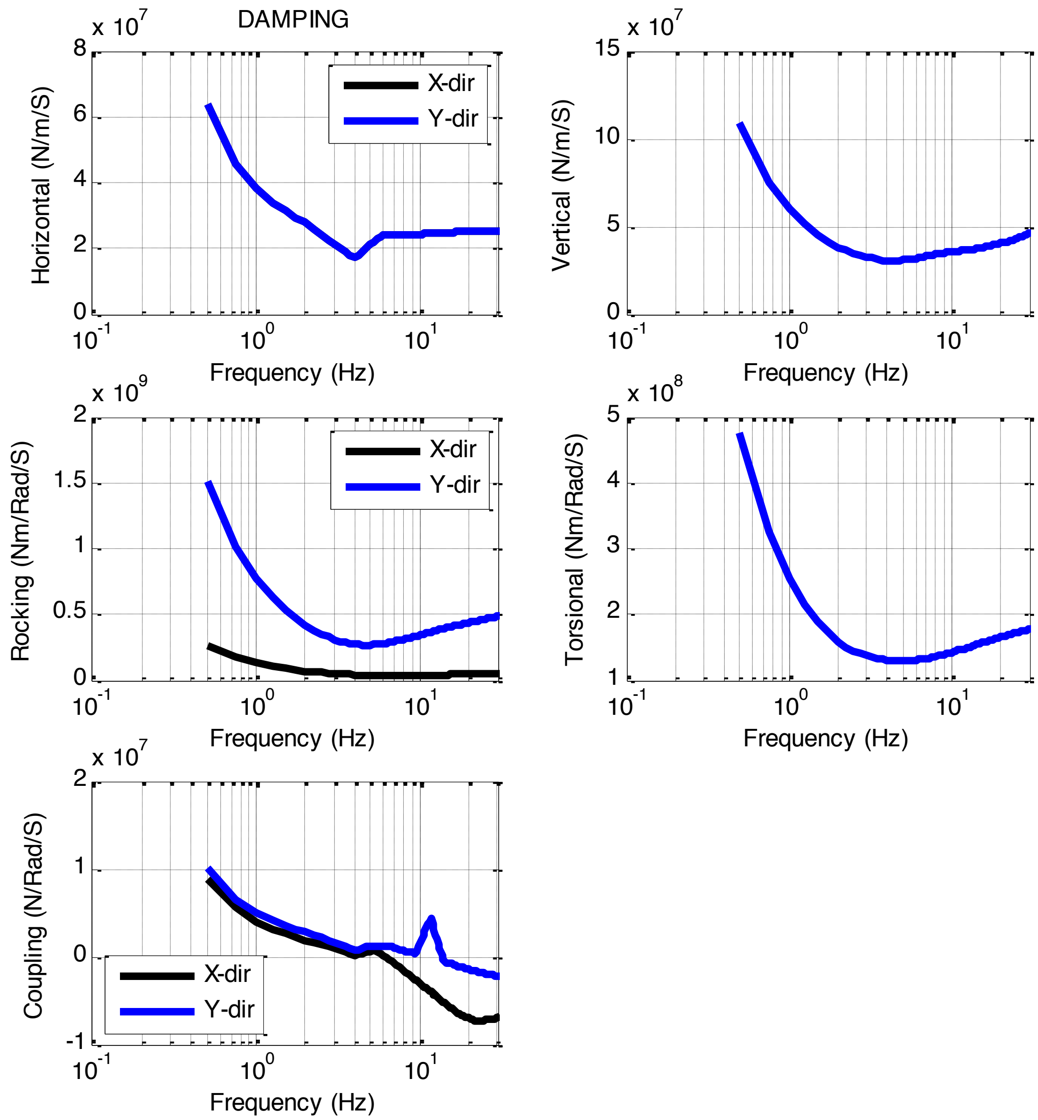


Figure 5.89: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

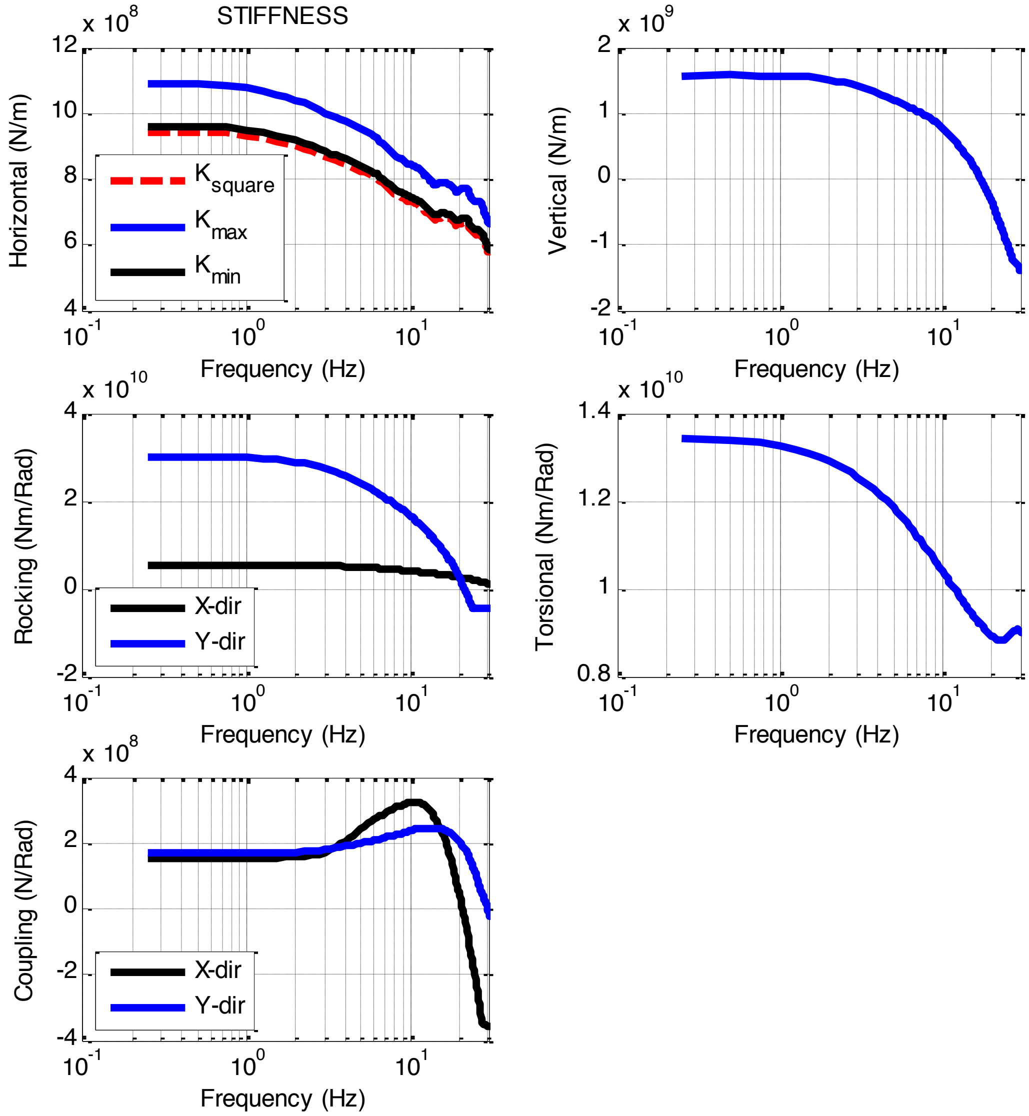


Figure 5.90: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

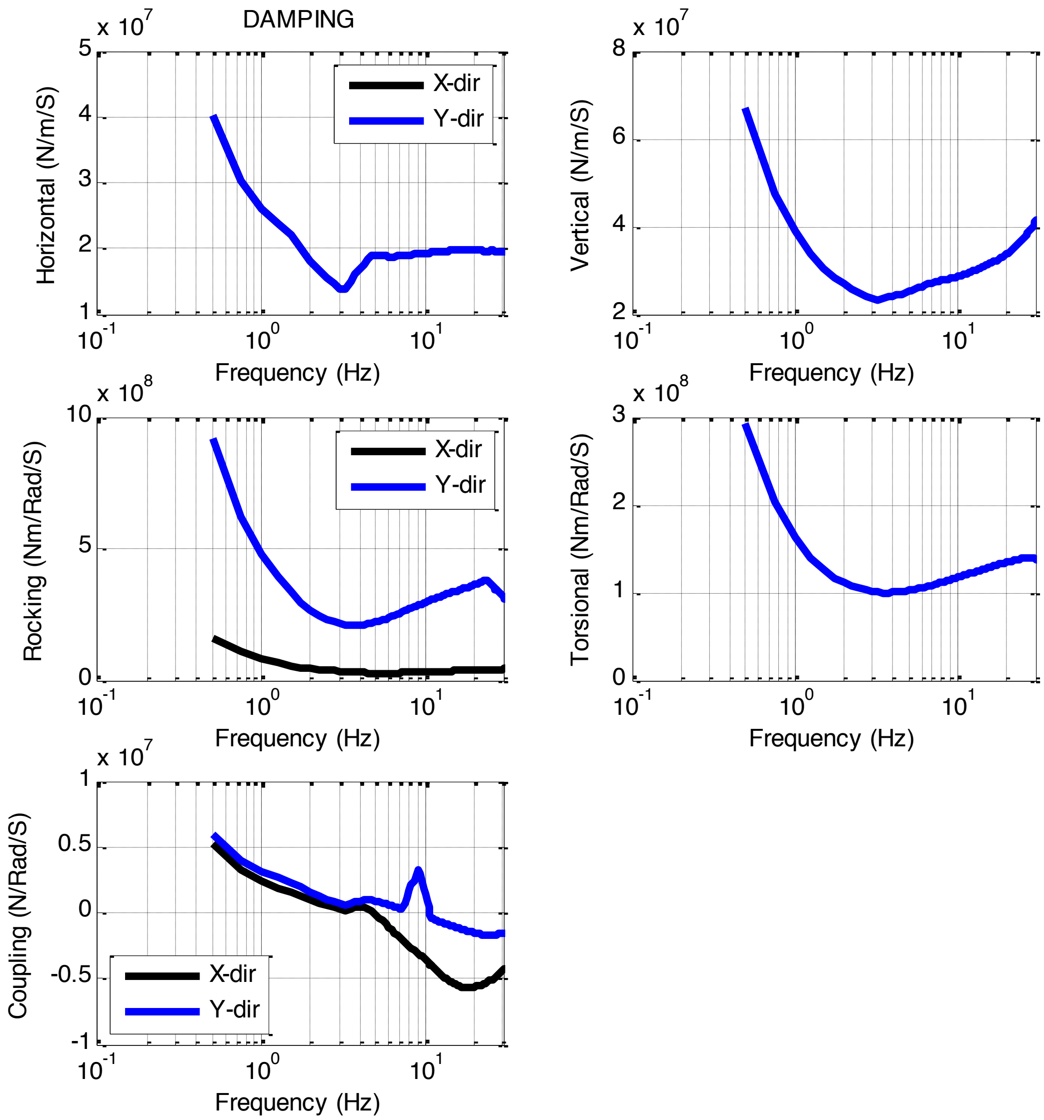


Figure 5.91: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

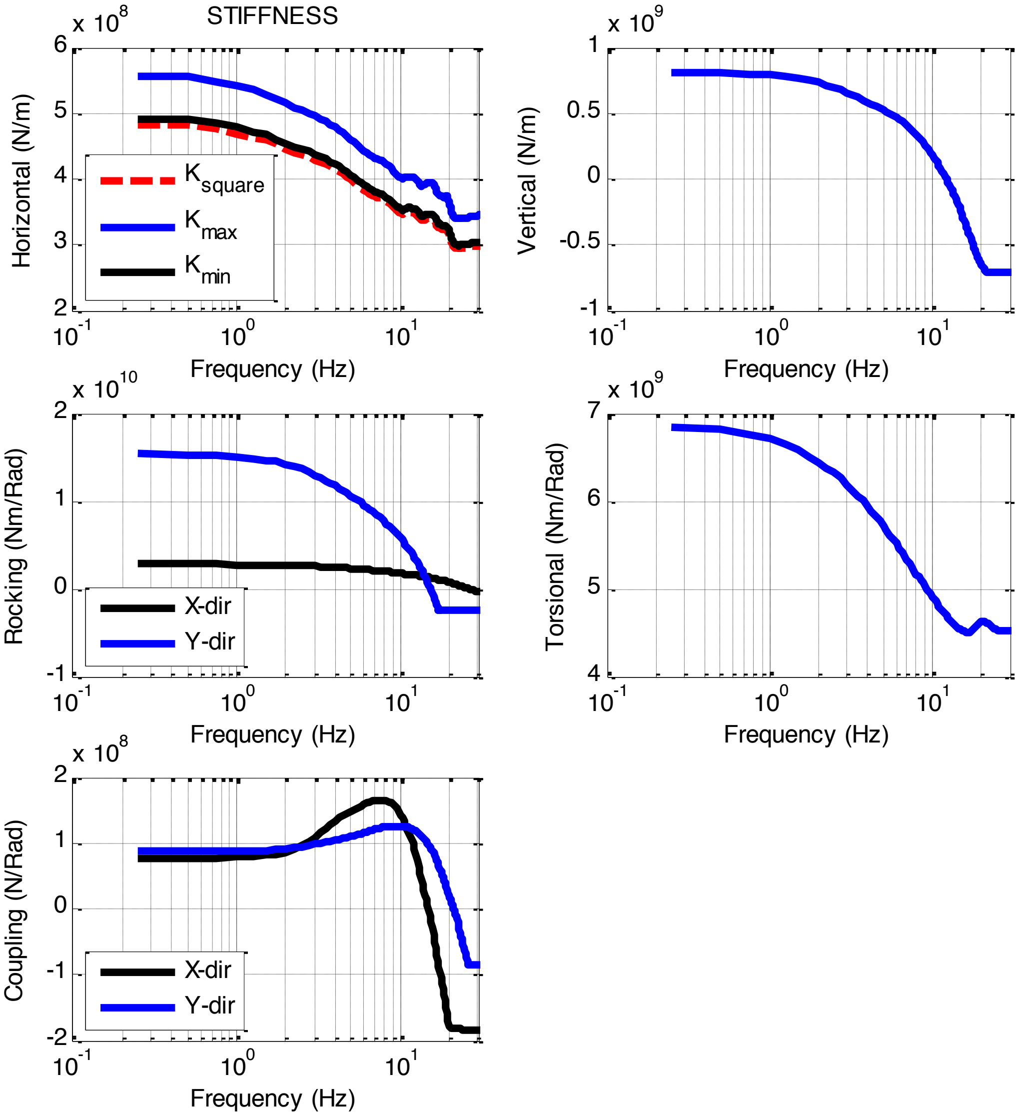


Figure 5.92: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

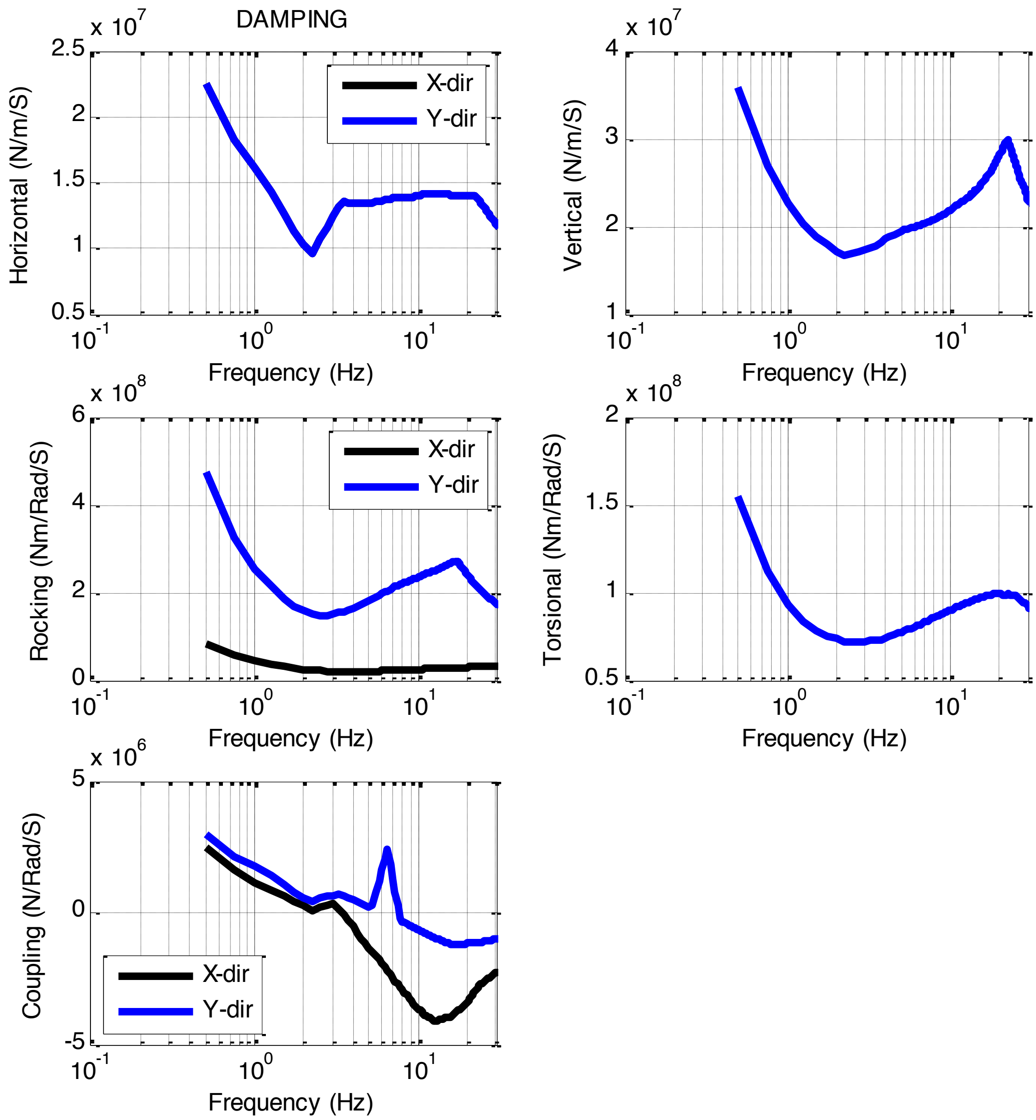


Figure 5.93: Terraced Building with 4 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

5.4 Terraced building, 6 Units – Concrete foundations

Figure 5.94 shows the scheme of the foundations of the Terraced building typology with 6 units. Hereinafter there are the impedance functions (in terms of frequency dependent stiffness and damping) of the building taking into account the three reference soil profiles defined in section 4.1.1 and the three scaling factors of section 4.1.2. The foundations characteristics are summarized in the following table.

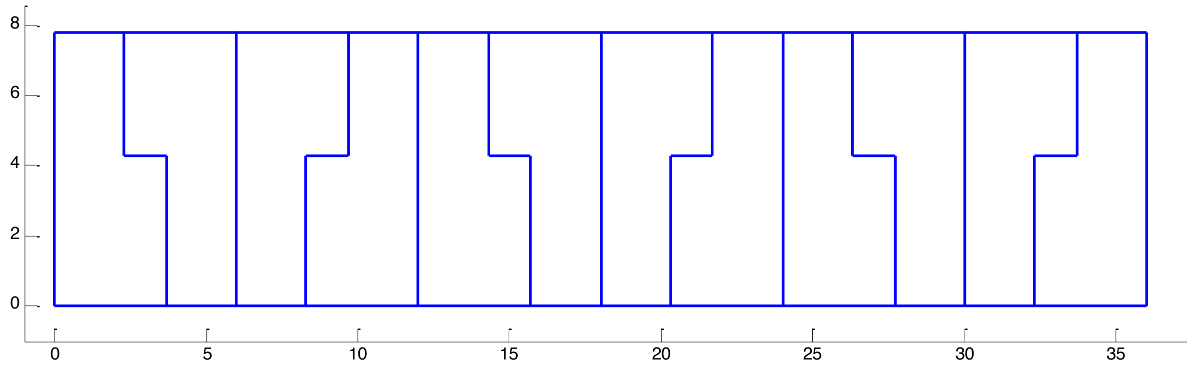


Figure 5.94: Terraced building, 6 units: schematic position of beam foundations

Table 5.6: Foundations characteristics of Terraced building, 6 Units – Concrete foundations

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m²]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m²]	I_{yy} [kg m²]	I_{zz} [kg m²]	I_{xy} [kg m²]	I_{xz} [kg m²]	I_{yz} [kg m²]
36	7.8	0.33	72.9	18.34	3.97	57.7e3	473.5e3	6338.9e3	6811.4e3	3.7e3	0	0

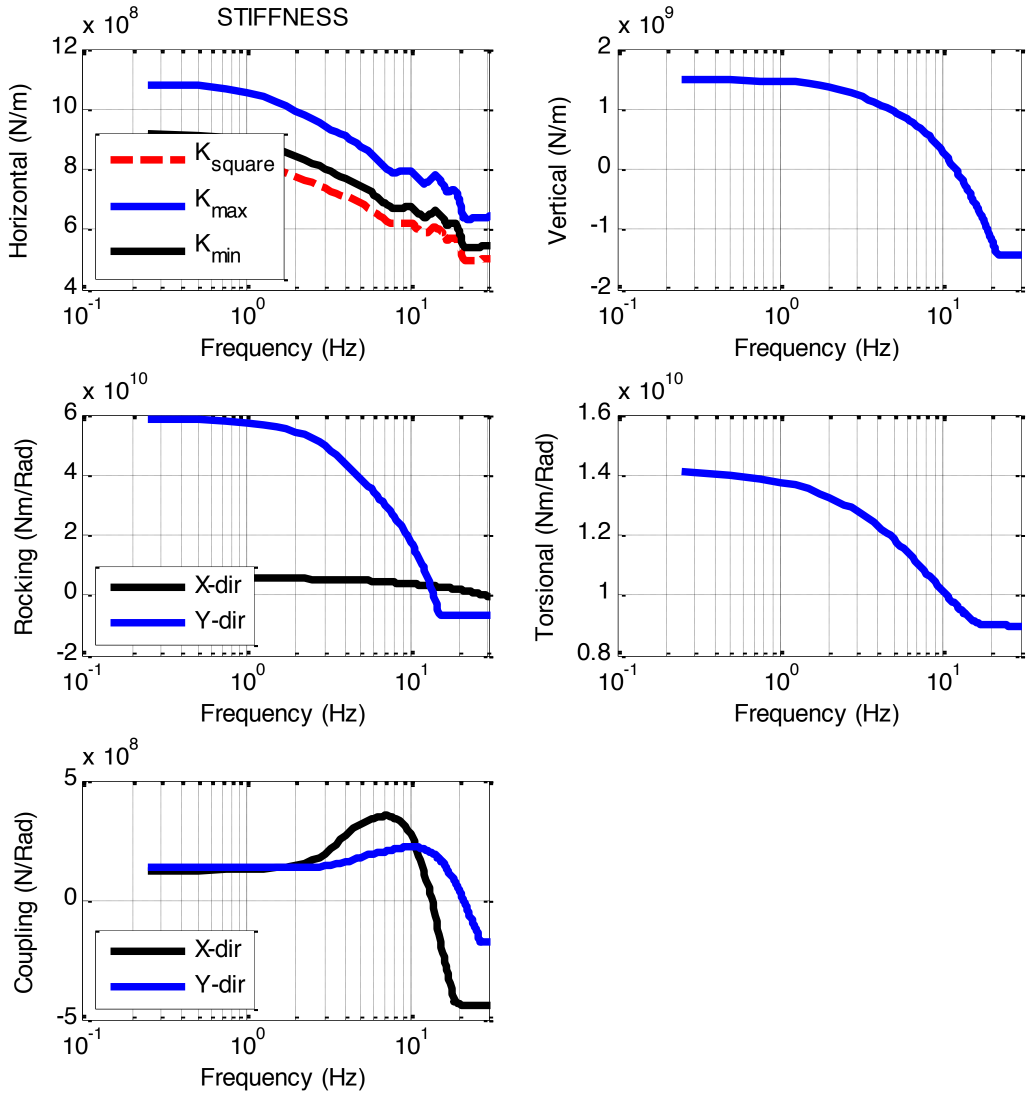


Figure 5.95: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: STIFFNESS

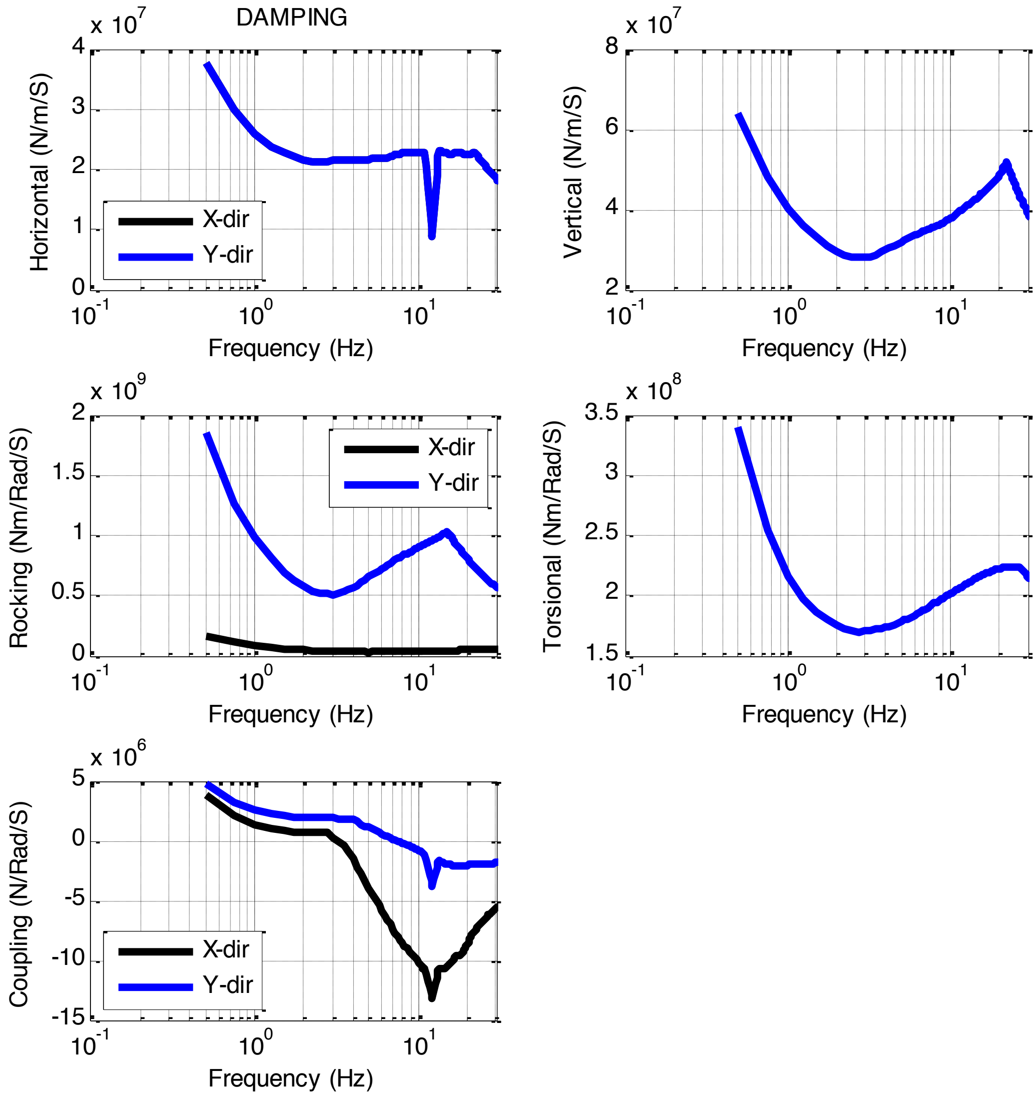


Figure 5.96: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: DAMPING

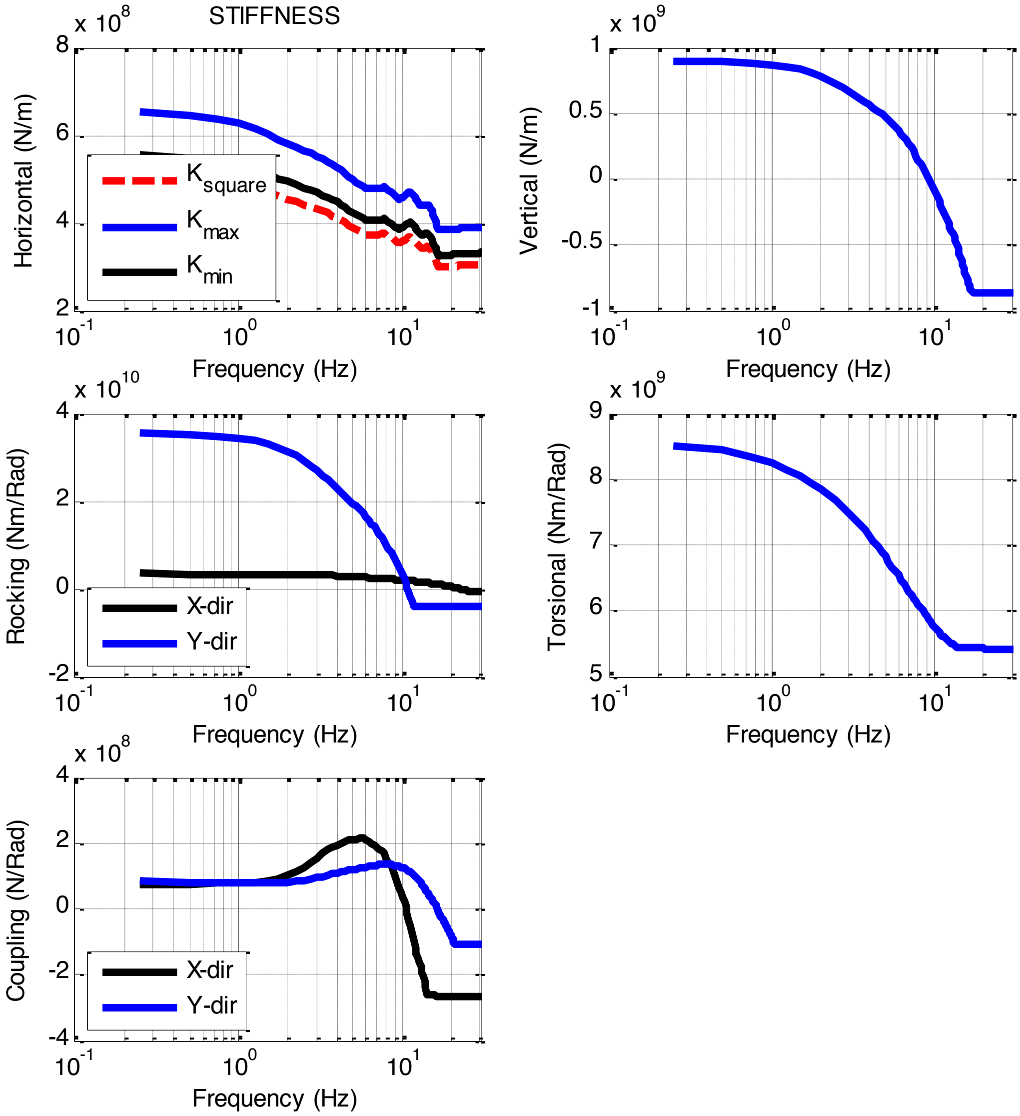


Figure 5.97: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: STIFFNESS

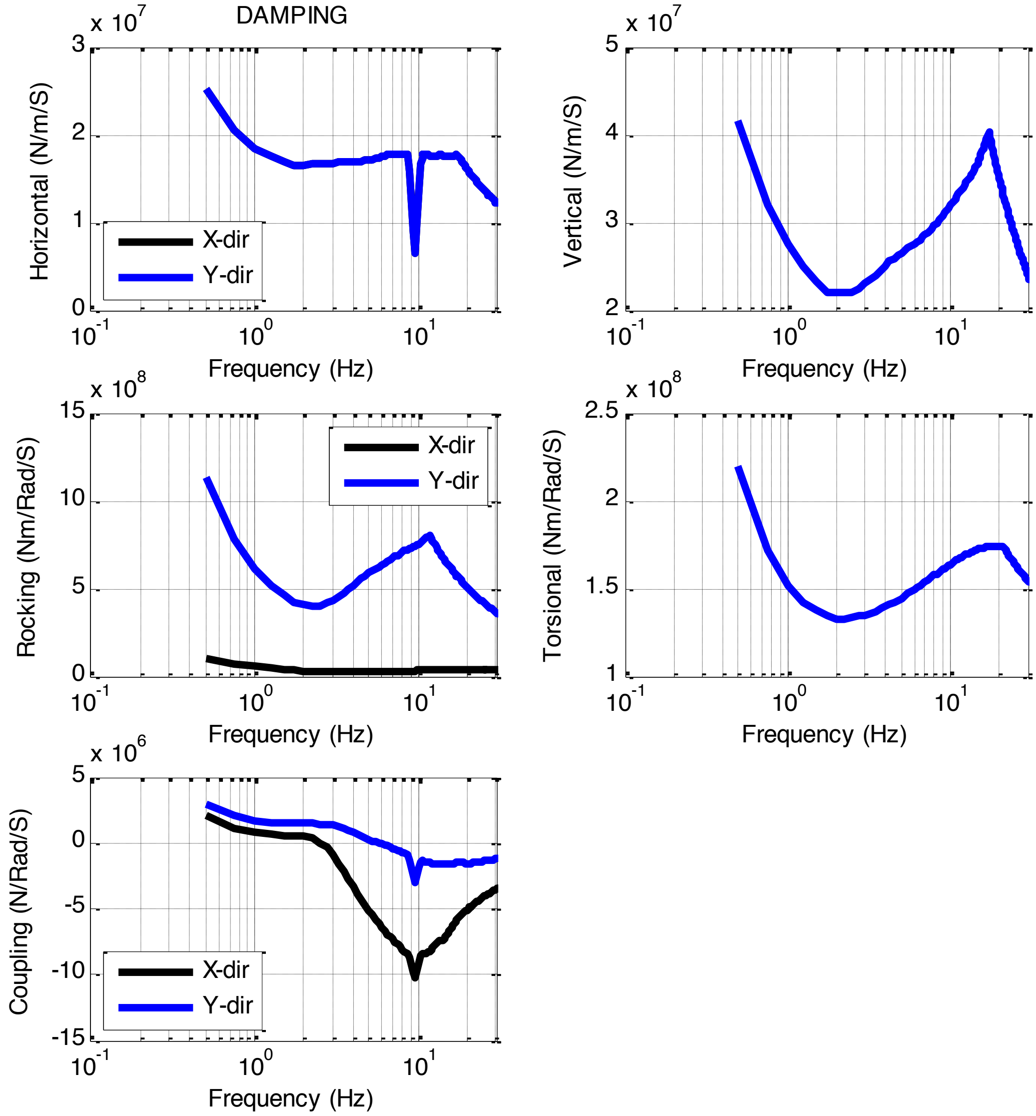


Figure 5.98: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: DAMPING

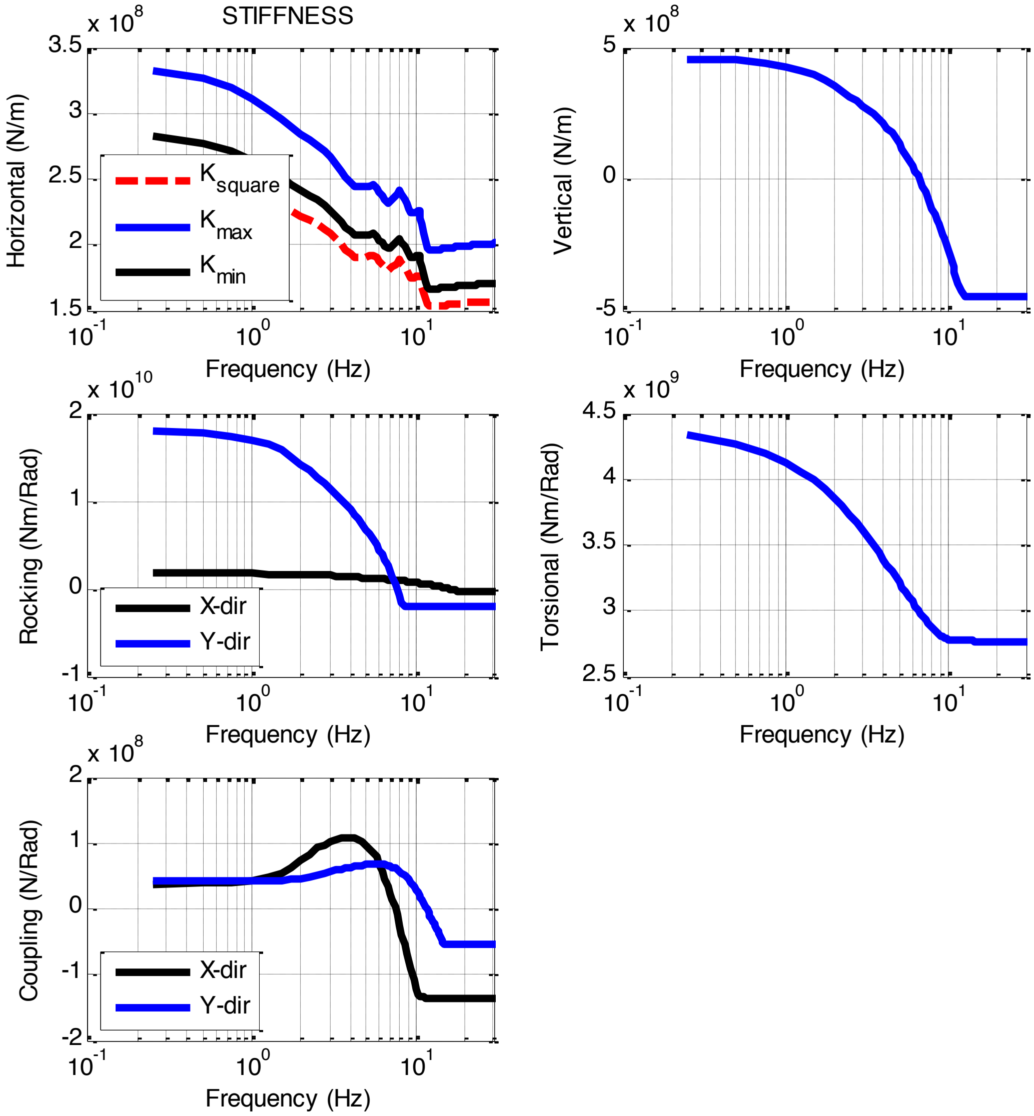


Figure 5.99: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: STIFFNESS

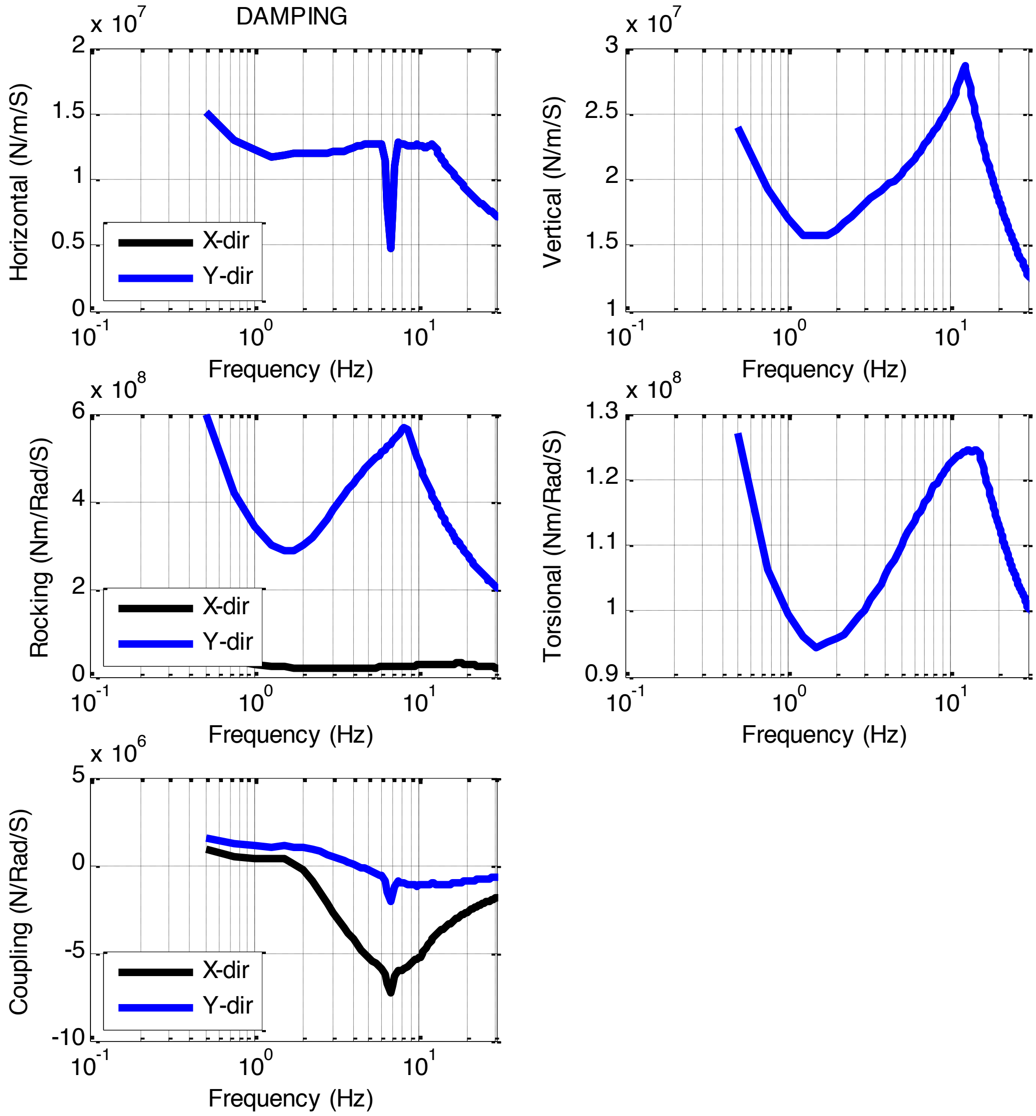


Figure 5.100: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: DAMPING

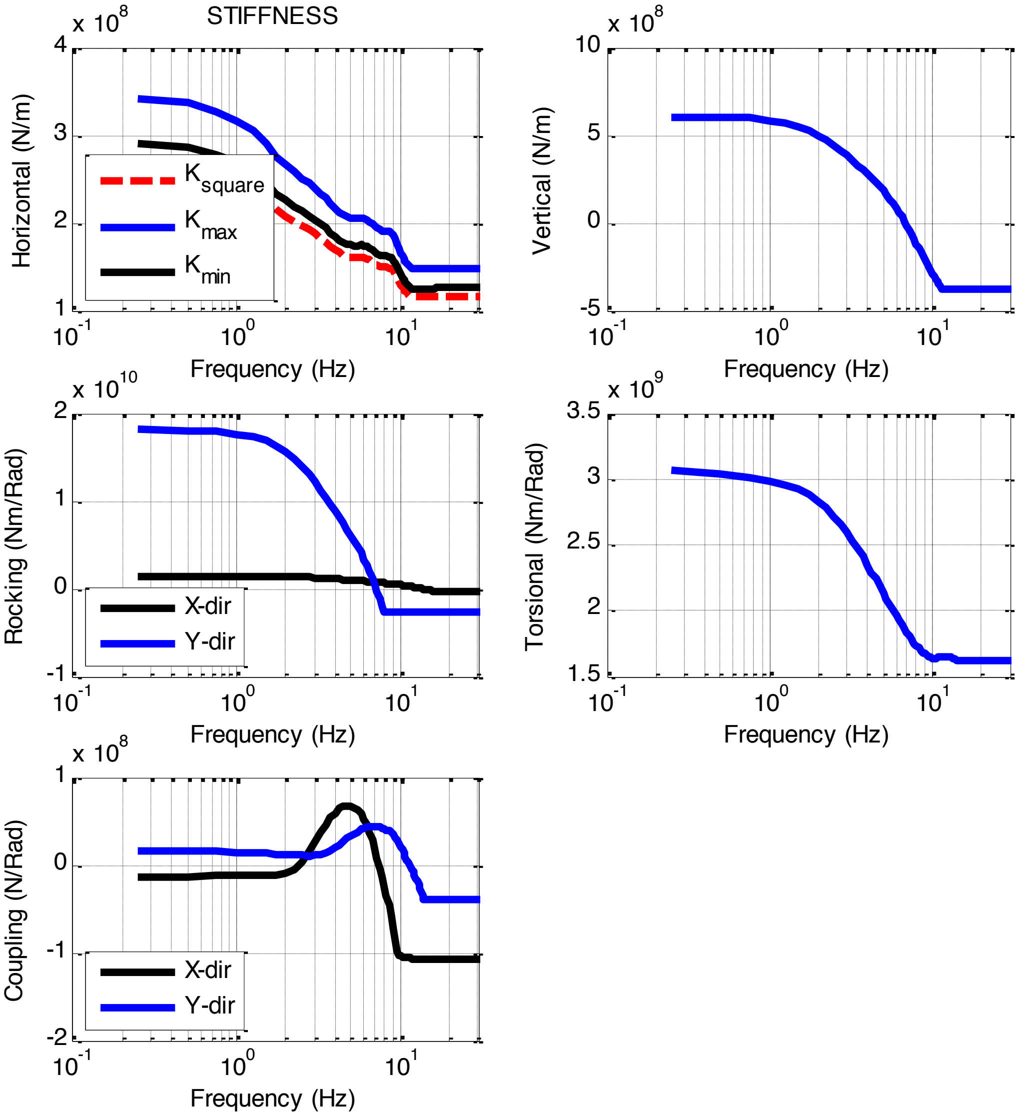


Figure 5.101: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

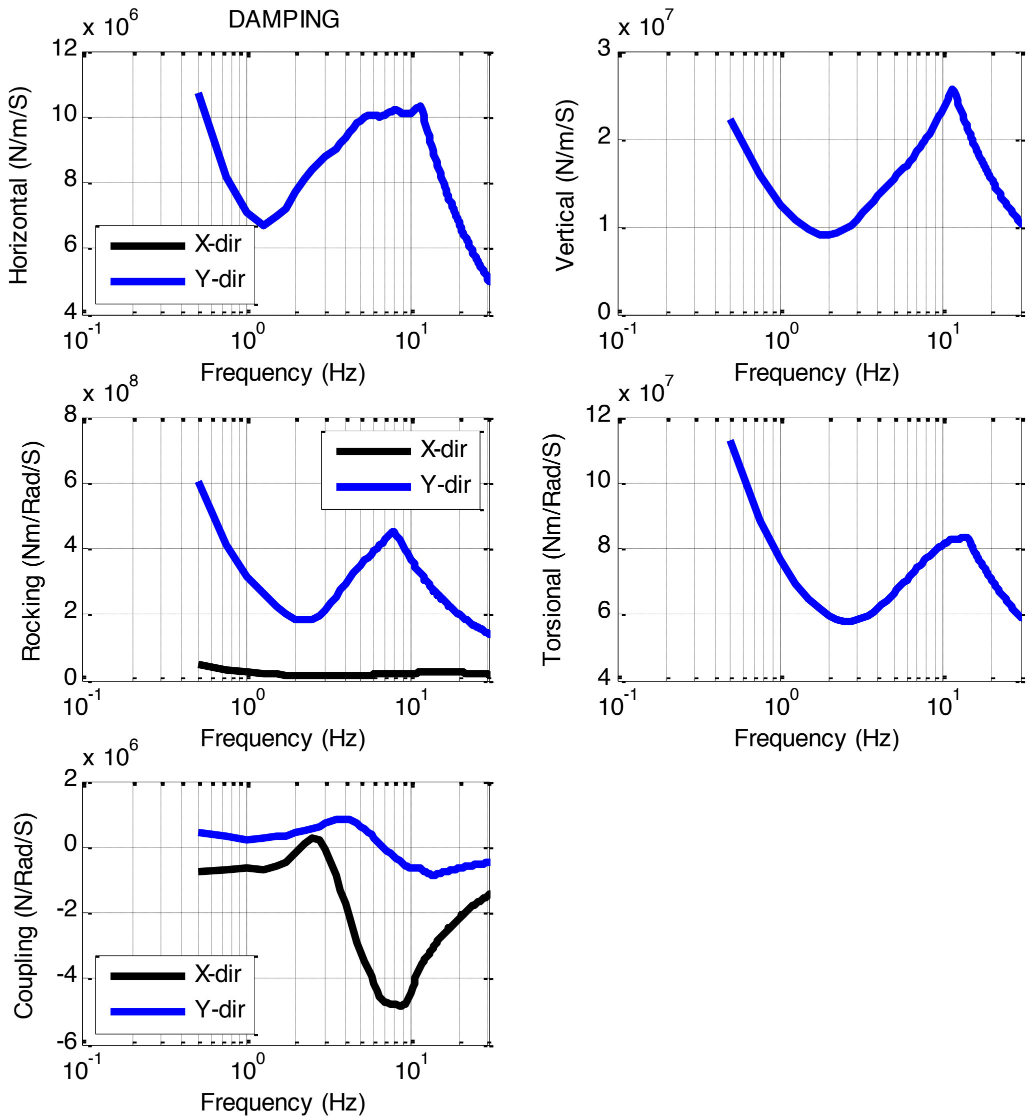


Figure 5.102: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

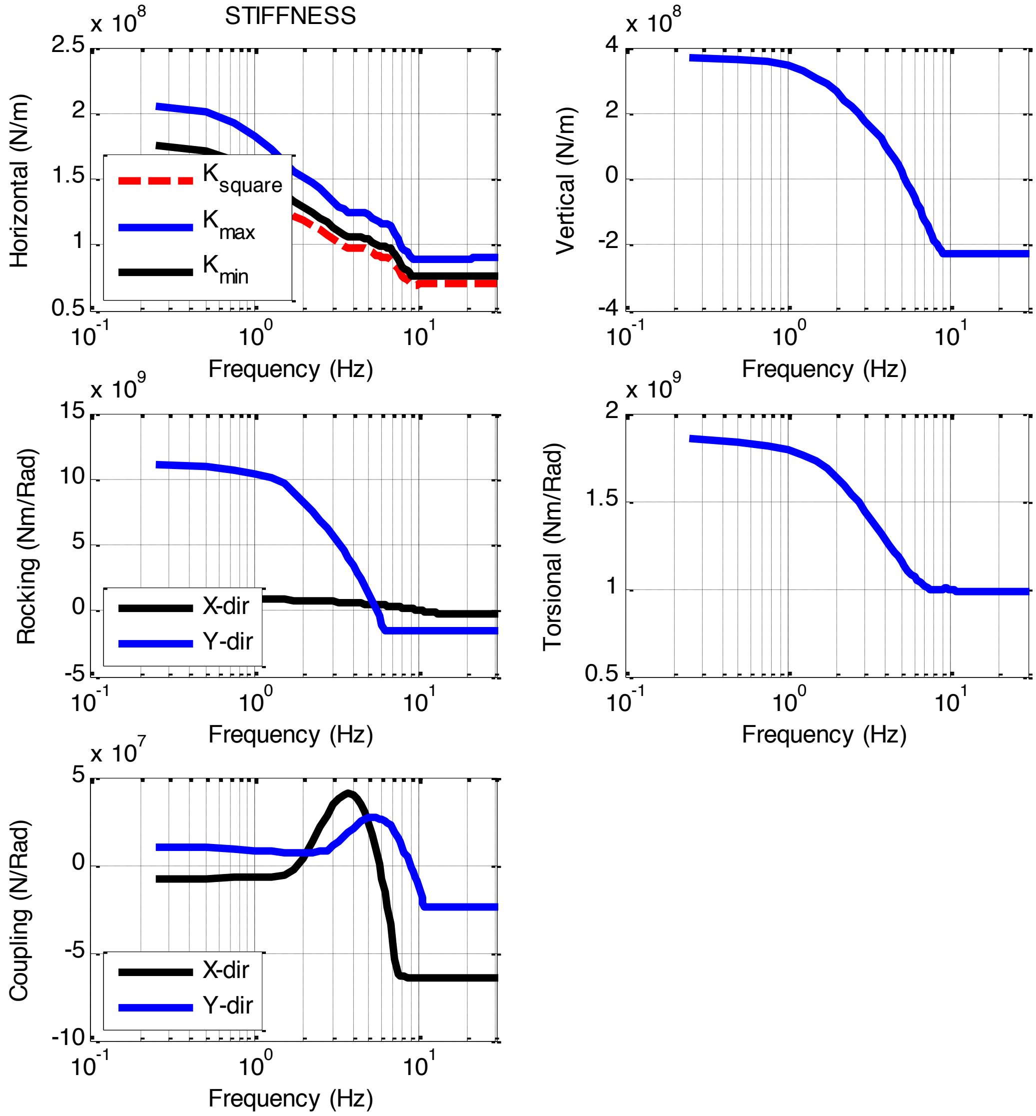


Figure 5.103: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

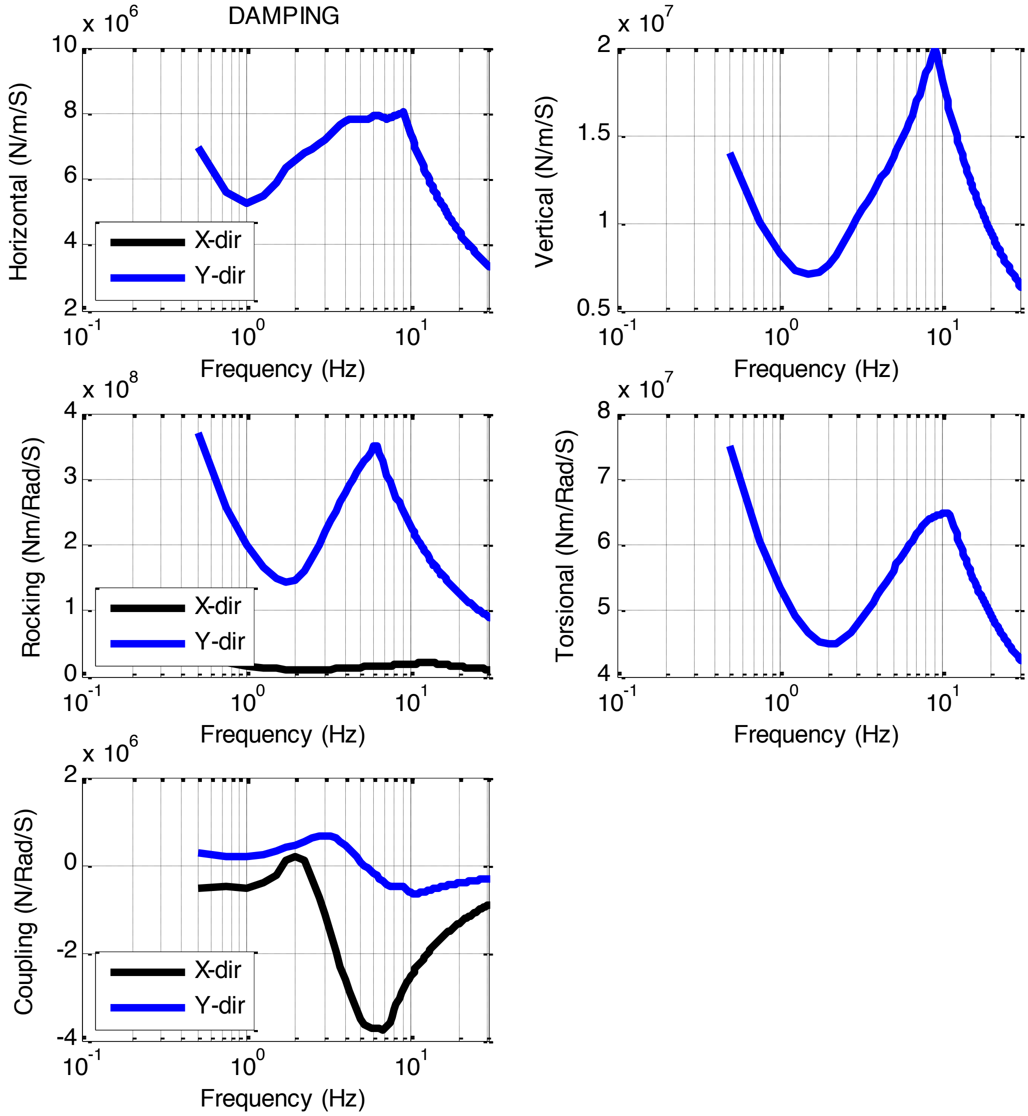


Figure 5.104: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

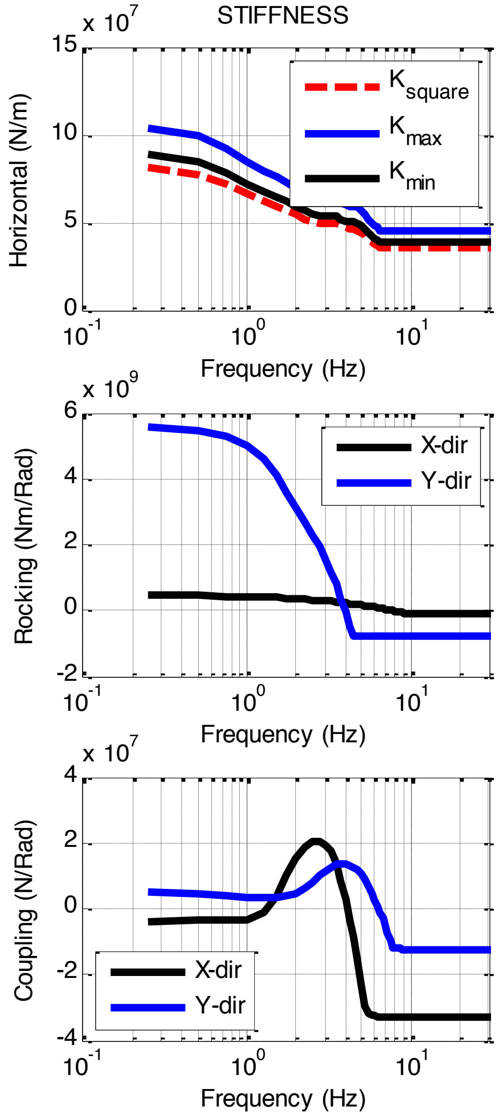


Figure 5.105: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

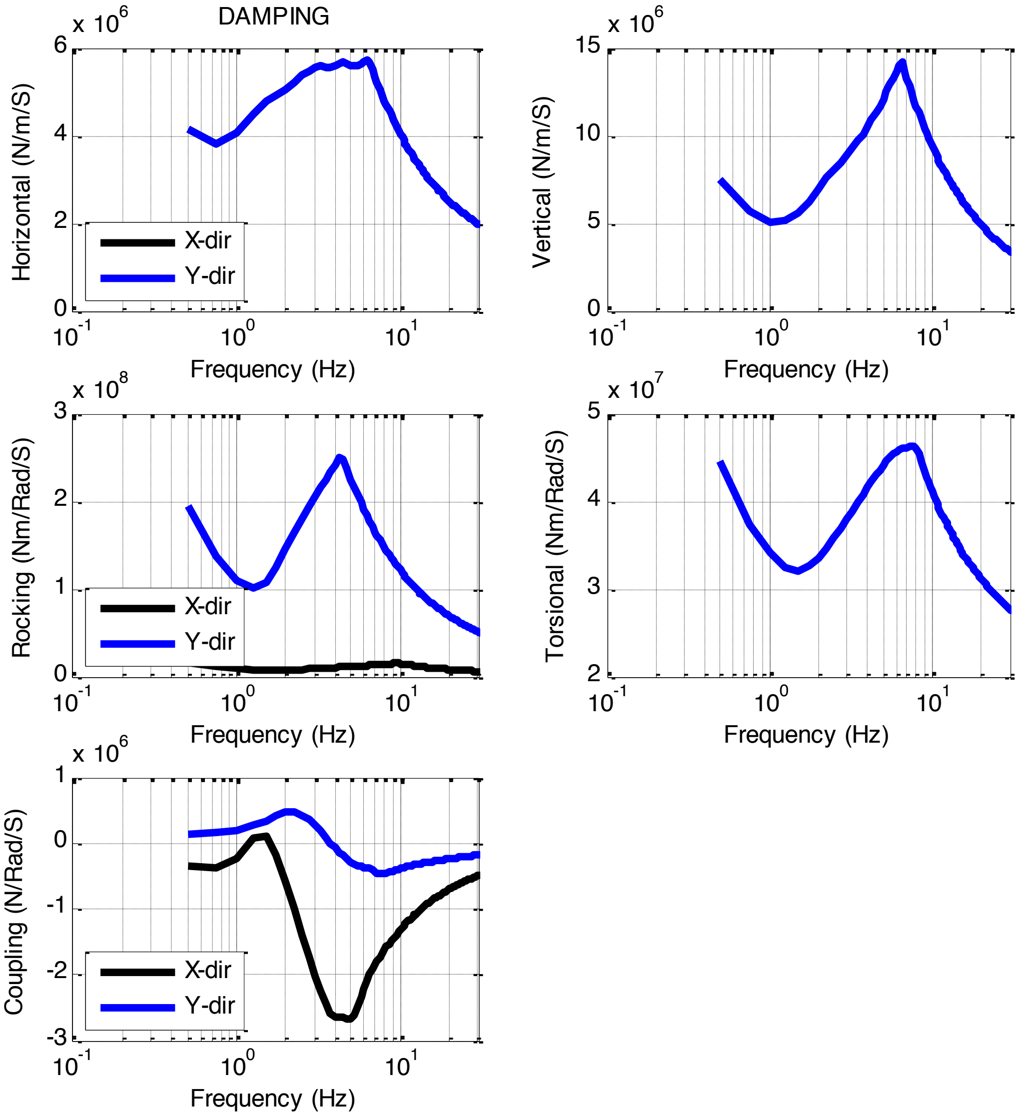


Figure 5.106: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

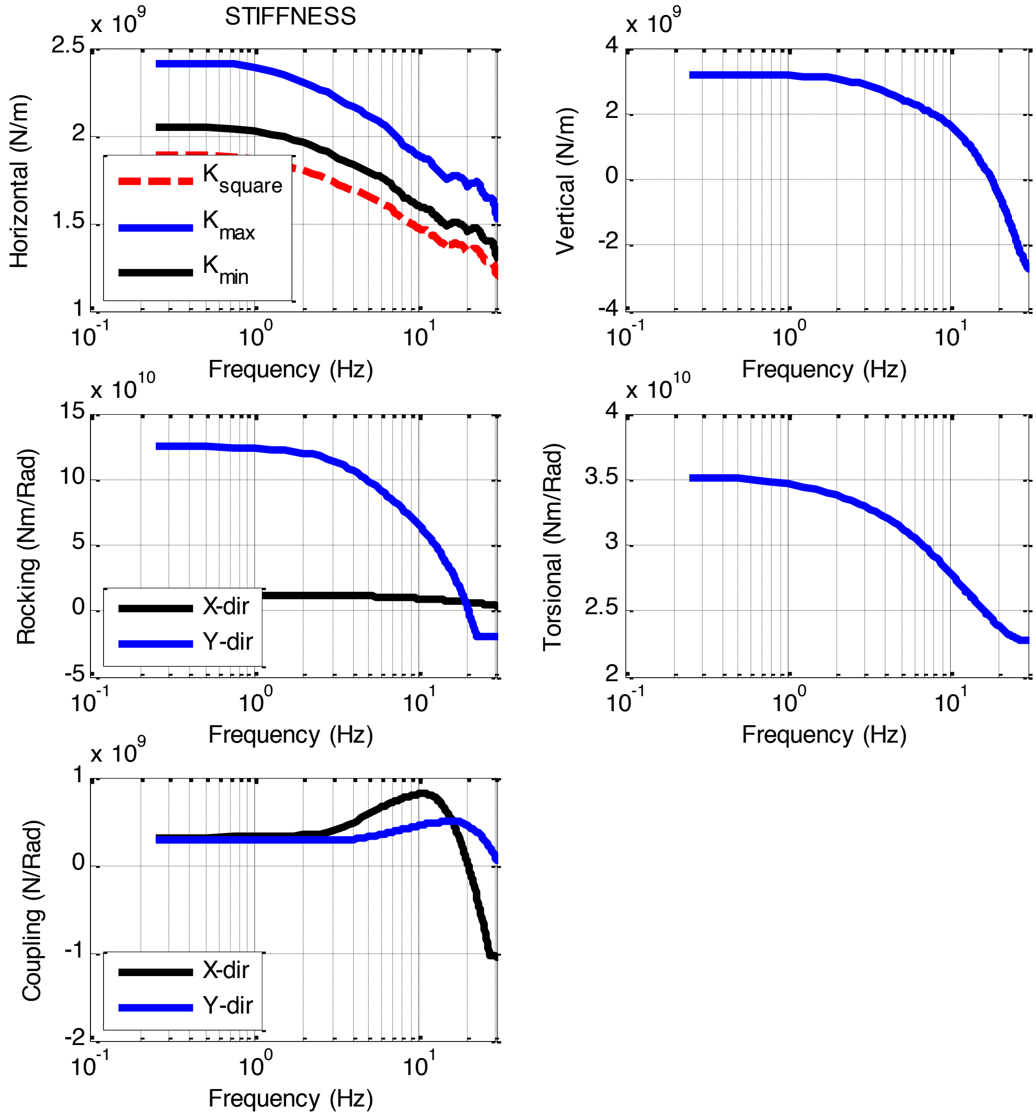


Figure 5.107: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

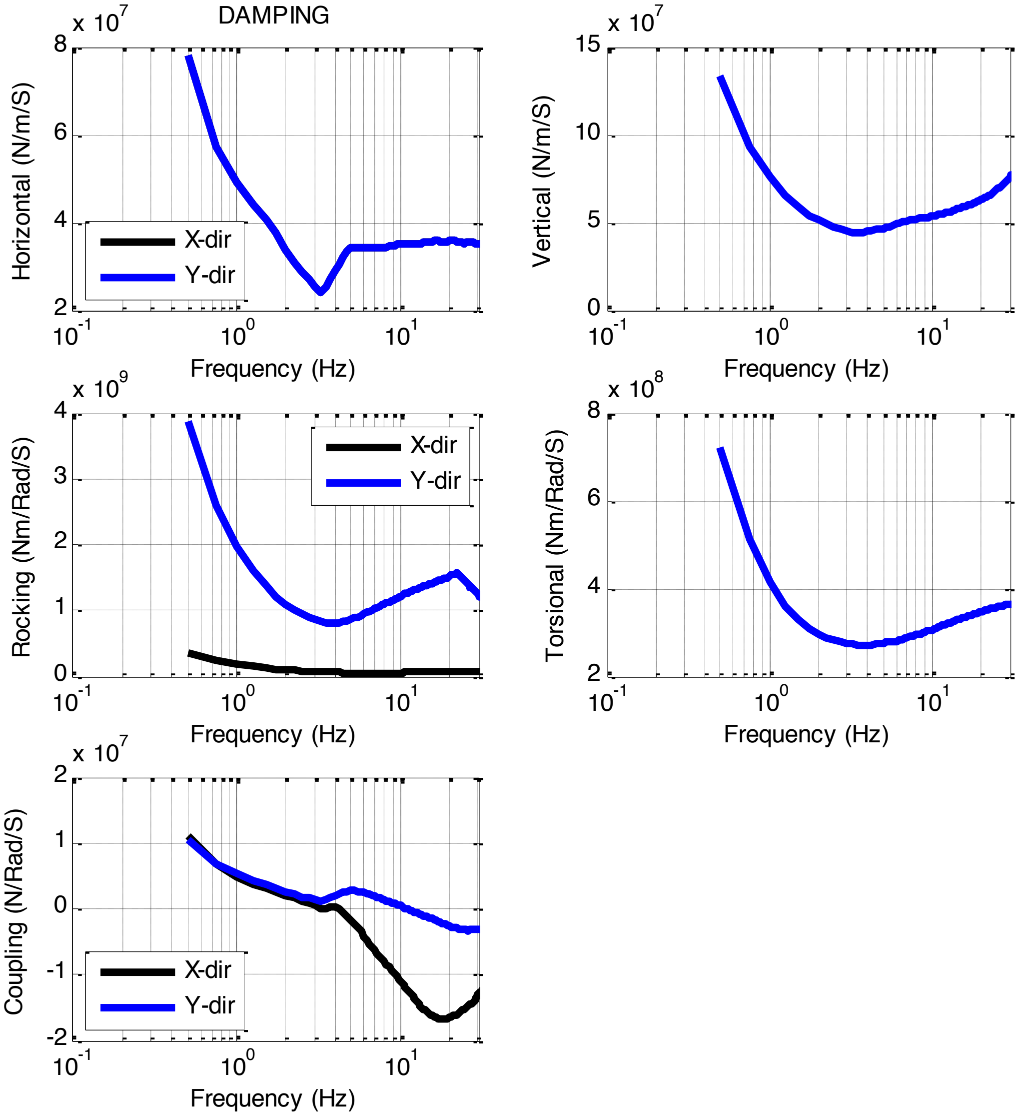


Figure 5.108: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

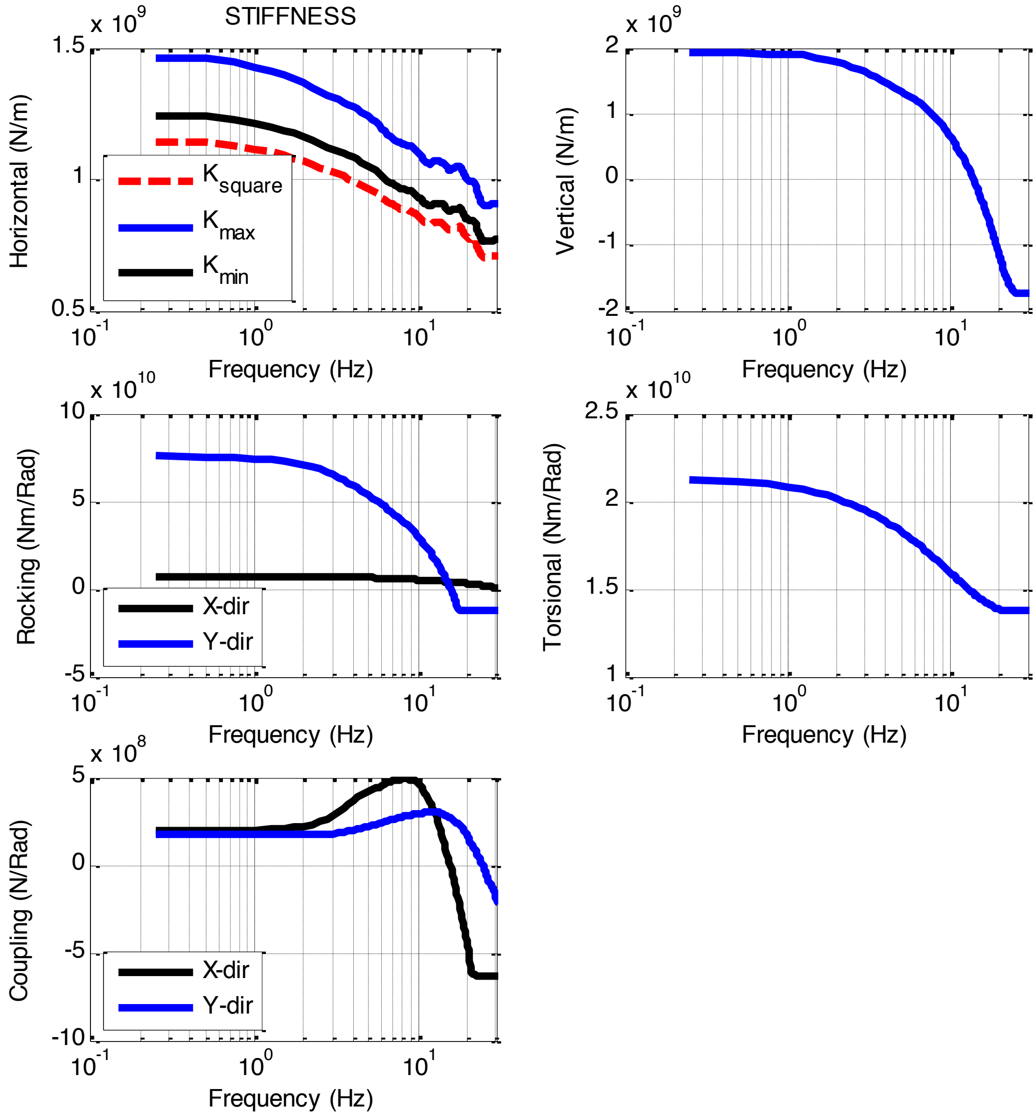


Figure 5.109: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

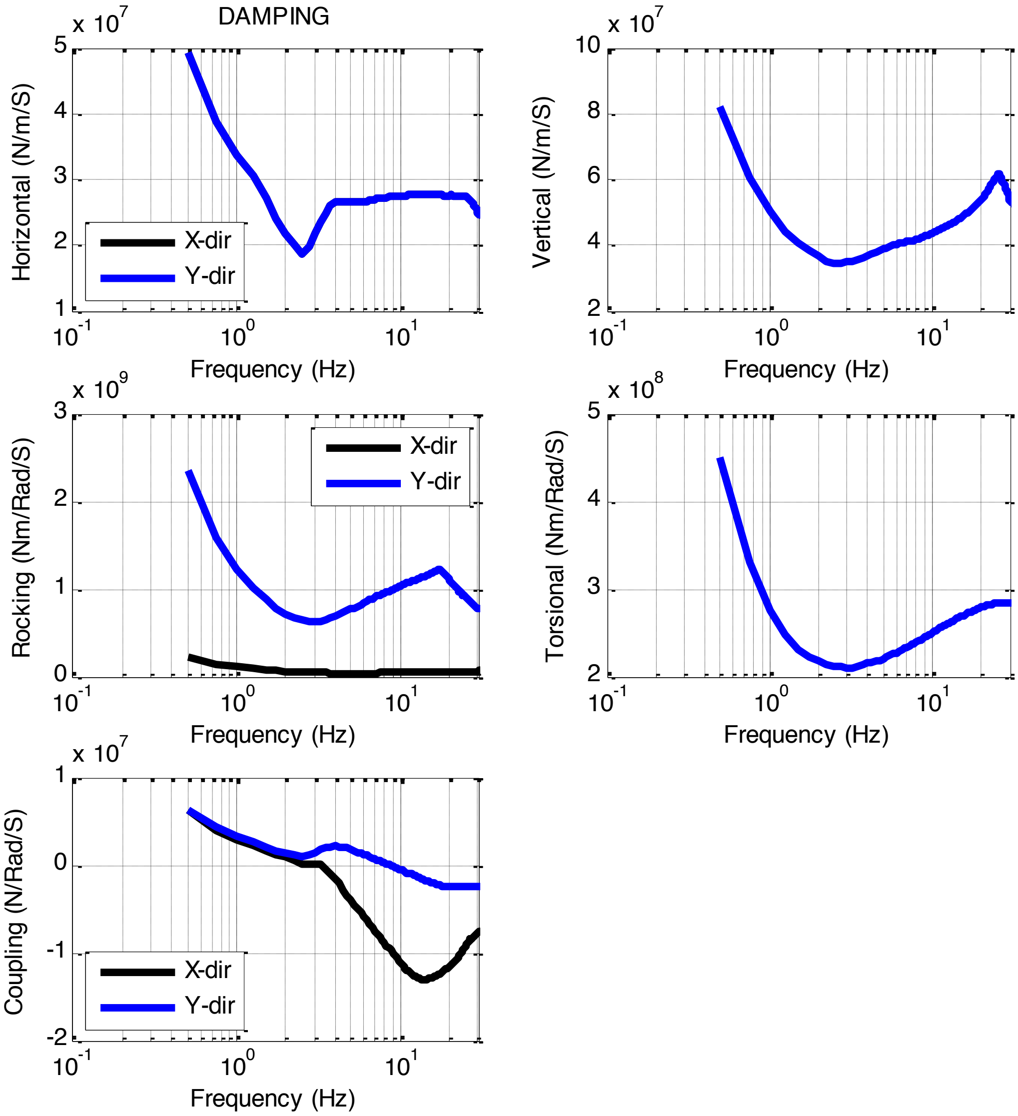


Figure 5.110: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

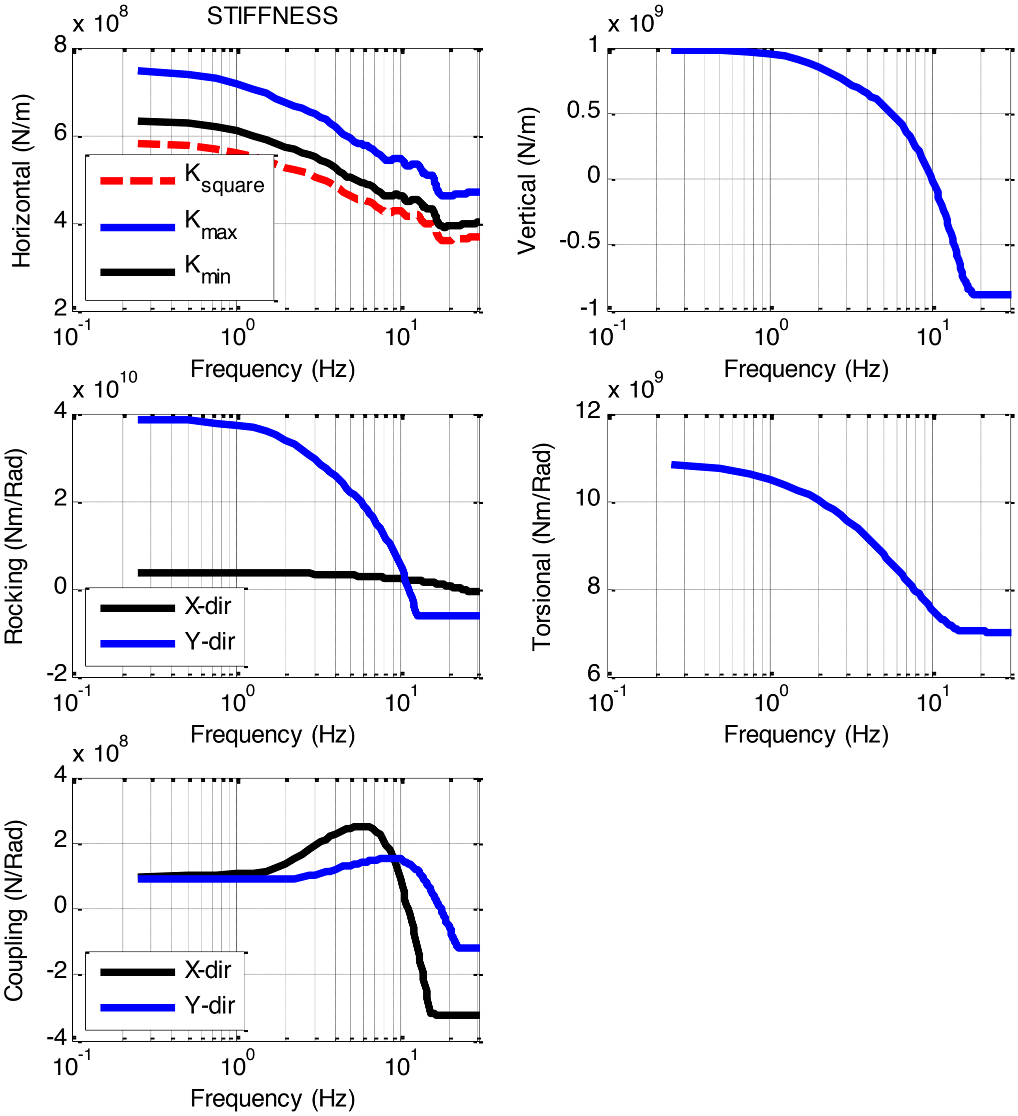


Figure 5.111: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

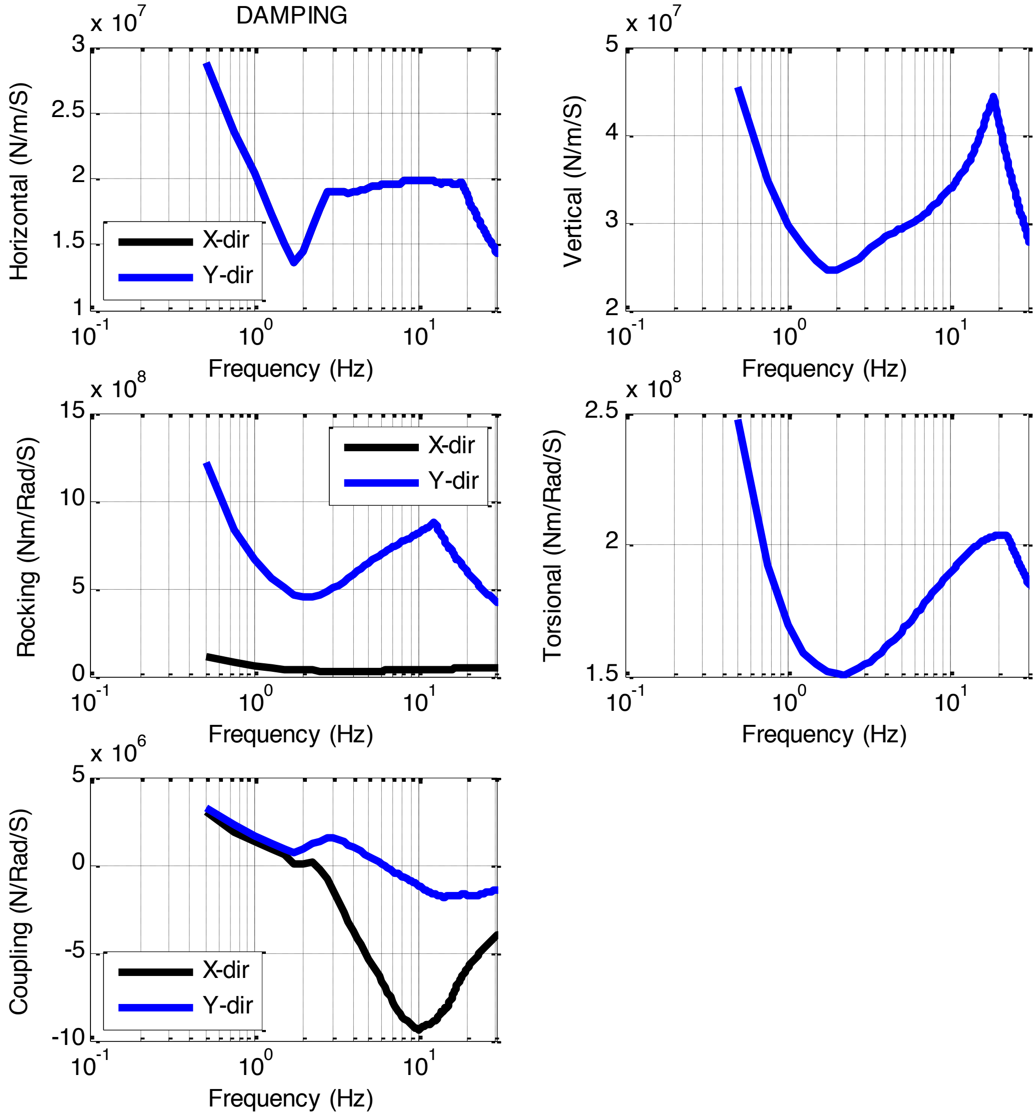


Figure 5.112: Terraced Building with 6 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

5.5 Terraced building, 8 Units – Concrete foundations

Figure 5.113 shows the scheme of the foundations of the Terraced building typology with 8 units. Hereinafter there are the impedance functions (in terms of frequency dependent stiffness and damping) of the building taking into account the three reference soil profiles defined in section 4.1.1 and the three scaling factors of section 4.1.2. The foundations characteristics are summarized in the following table.

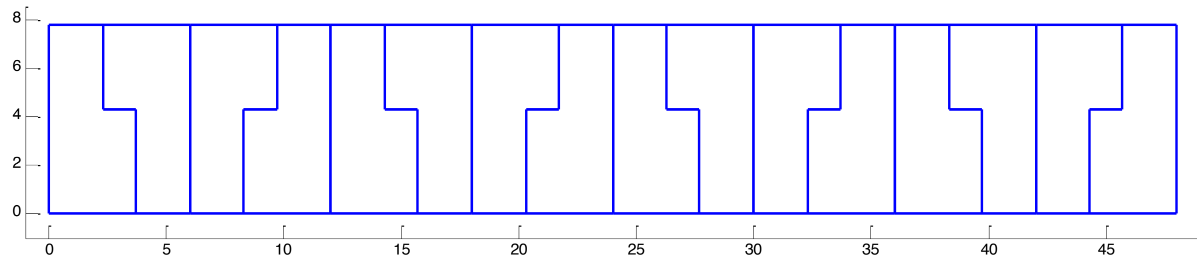


Figure 5.113: Terraced building, 8 units: schematic position of beam foundations

Table 5.7: Foundations characteristics of Terraced building, 8 Units – Concrete foundations

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m²]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m²]	I_{yy} [kg m²]	I_{zz} [kg m²]	I_{xy} [kg m²]	I_{xz} [kg m²]	I_{yz} [kg m²]
48	7.8	0.33	97.2	24.45	3.97	77.0e3	631.4e3	14916.2e3	15546.2e3	4.9e3	0	0

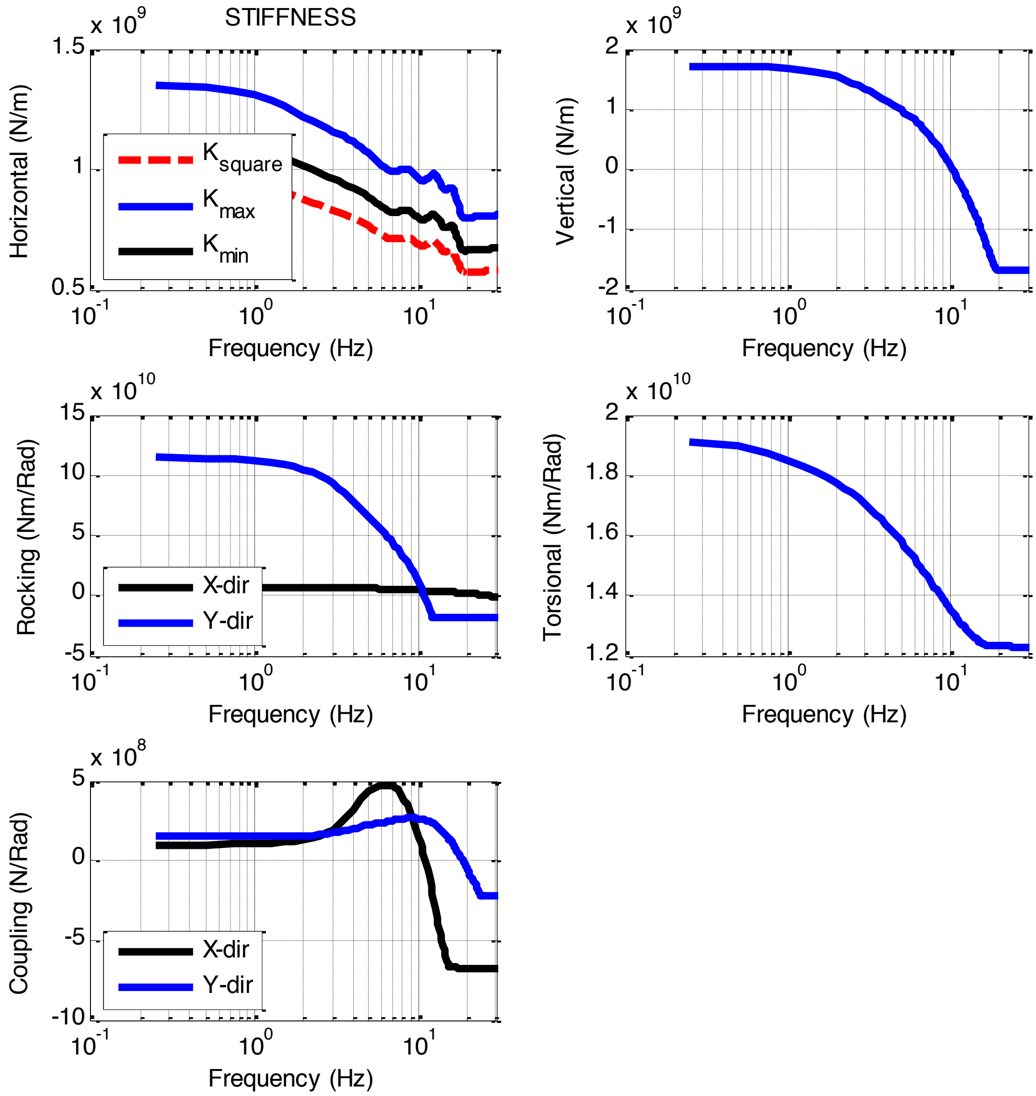


Figure 5.114: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: STIFFNESS

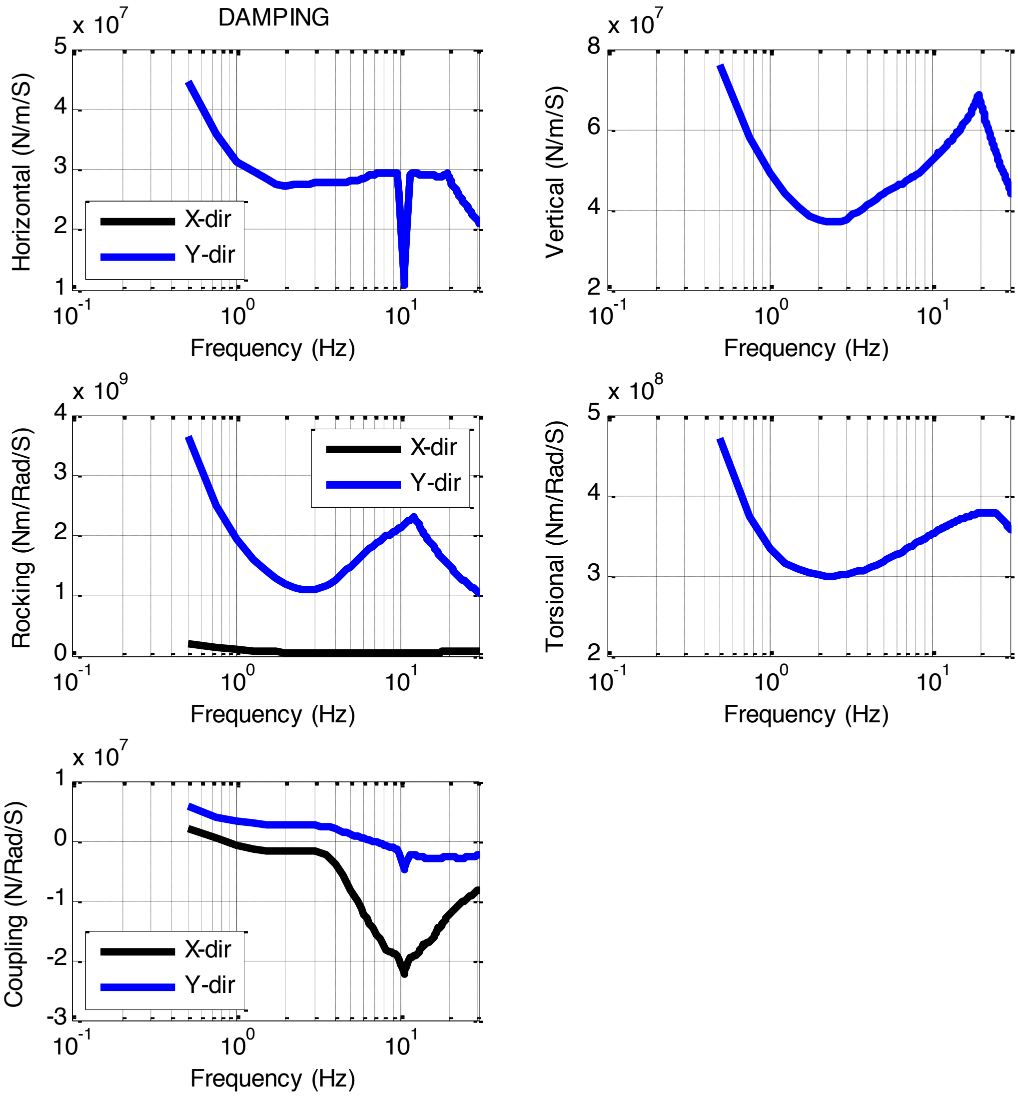


Figure 5.115: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF1: DAMPING

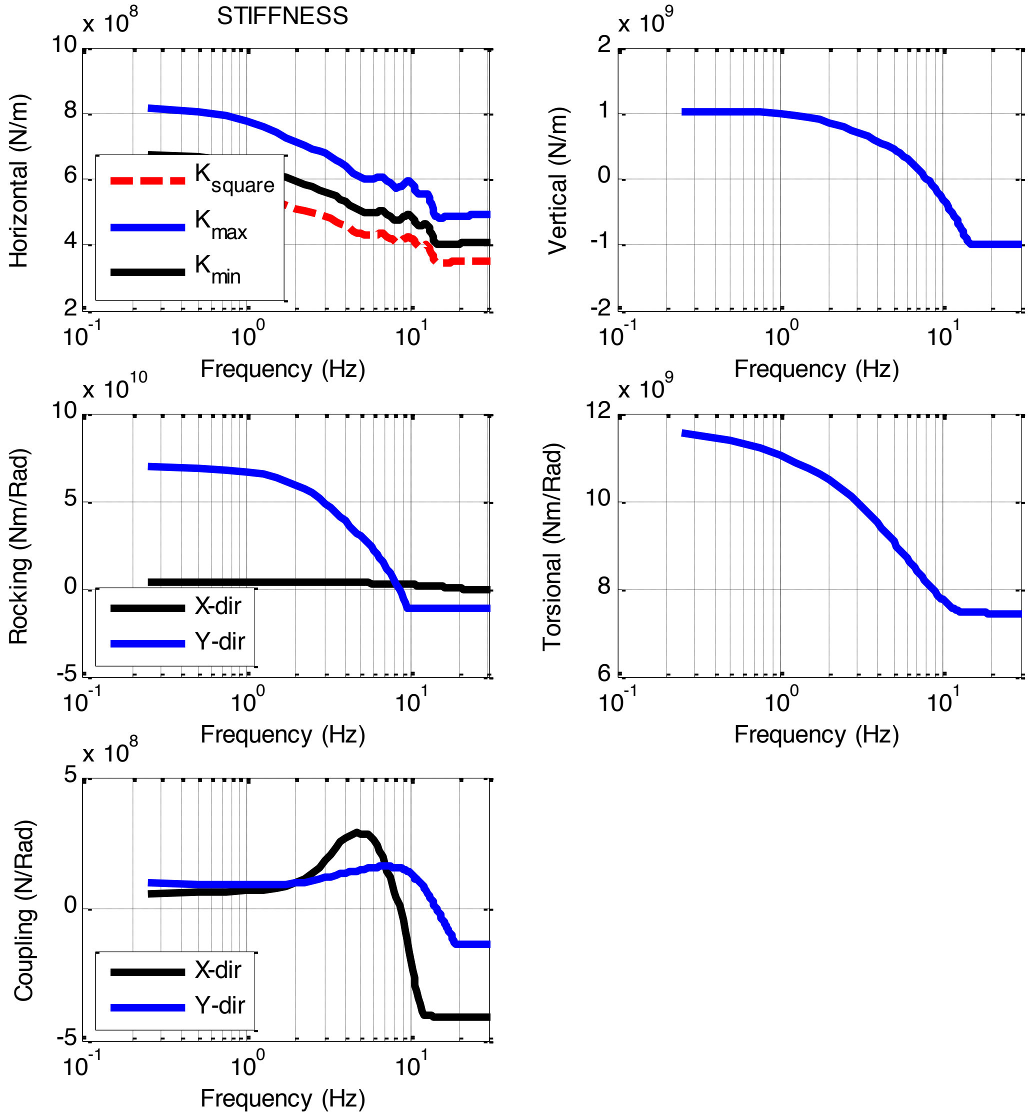


Figure 5.116: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: STIFFNESS

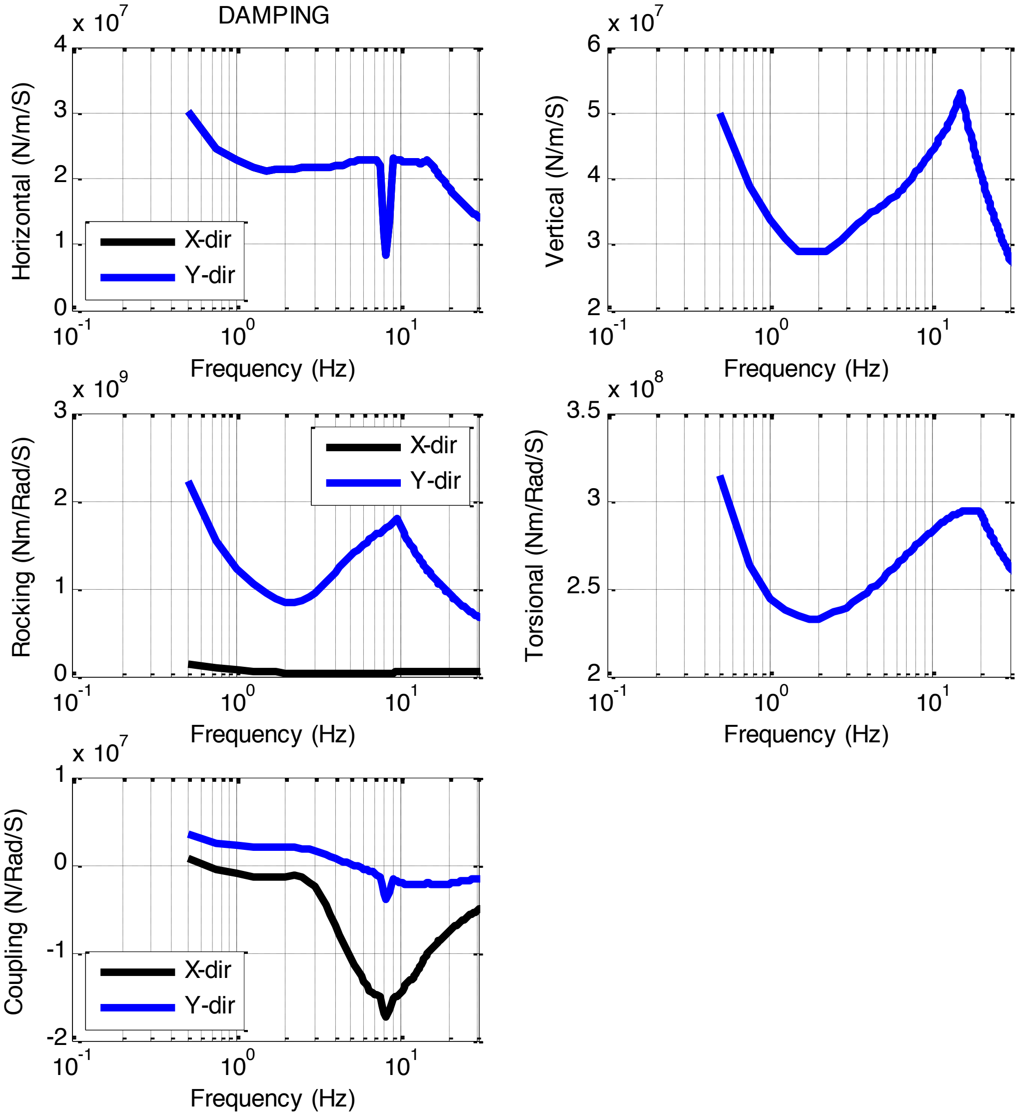


Figure 5.117: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF2: DAMPING

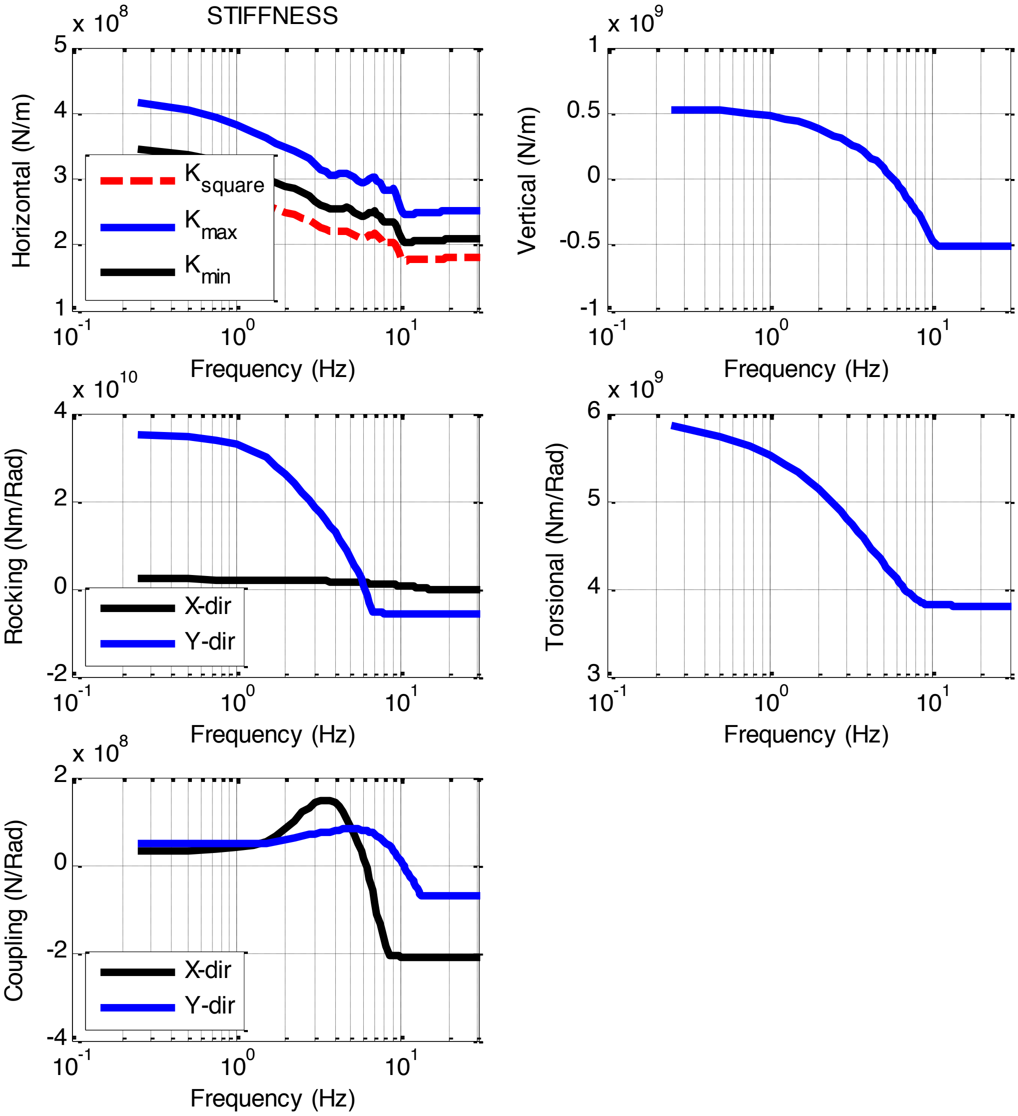


Figure 5.118: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: STIFFNESS

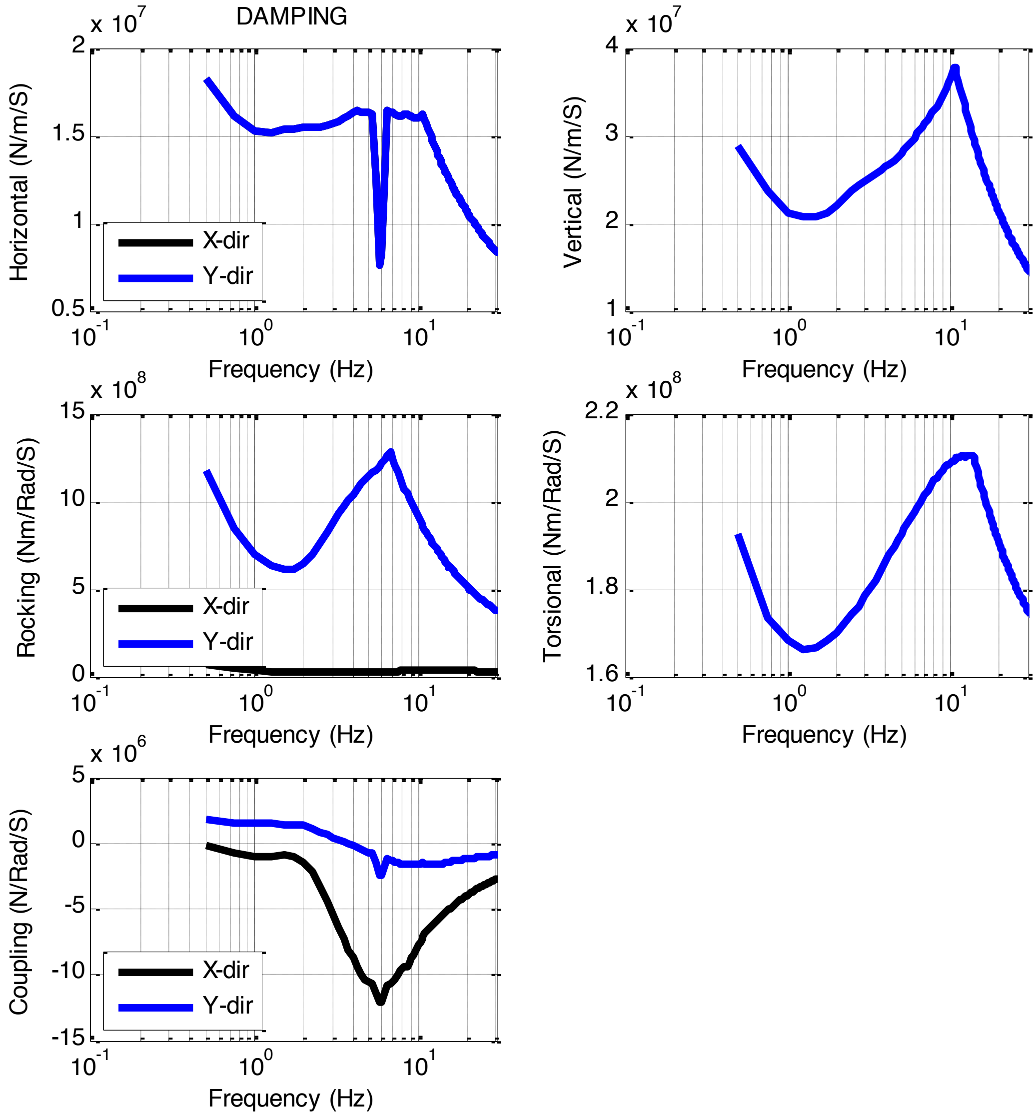


Figure 5.119: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean V_S profile with scaling factor SF3: DAMPING

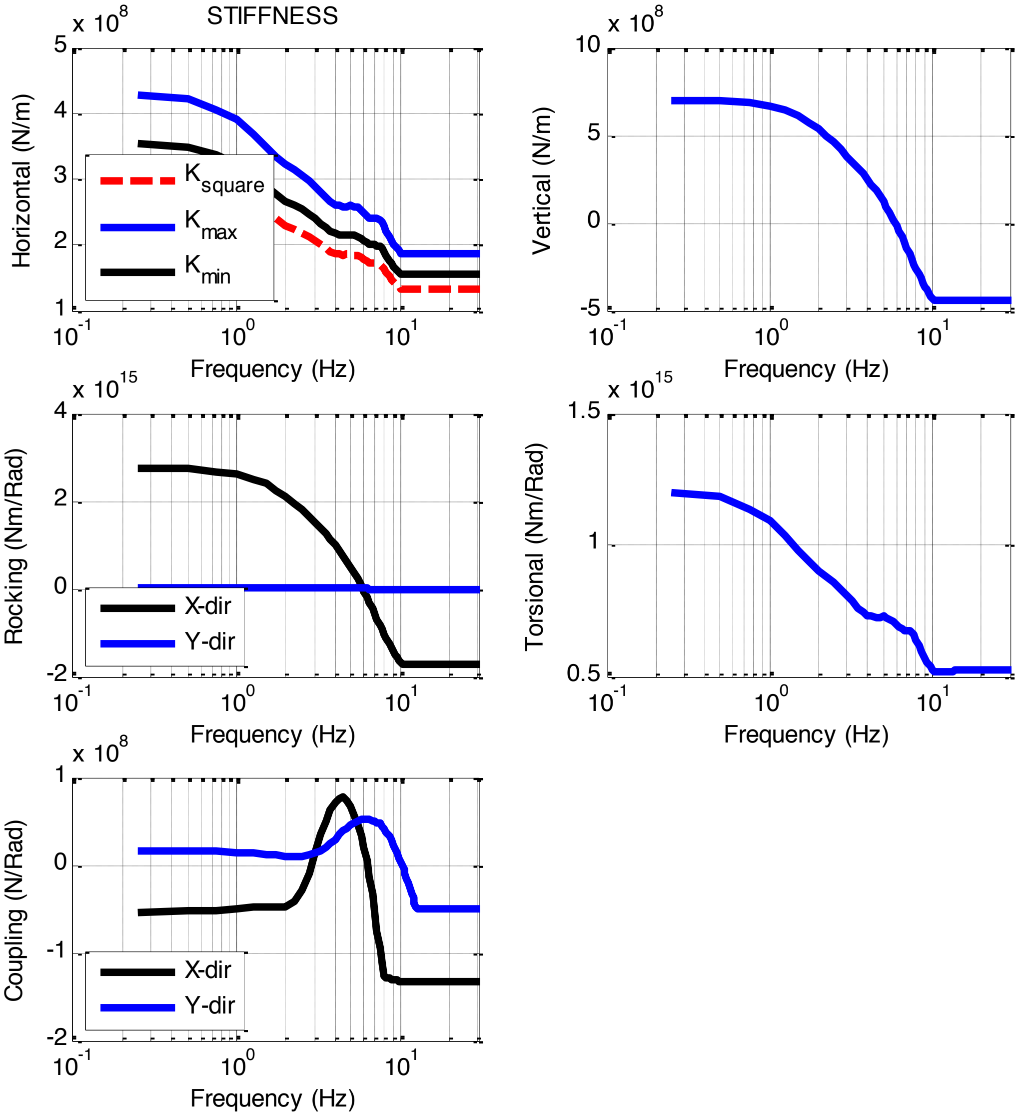


Figure 5.120: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

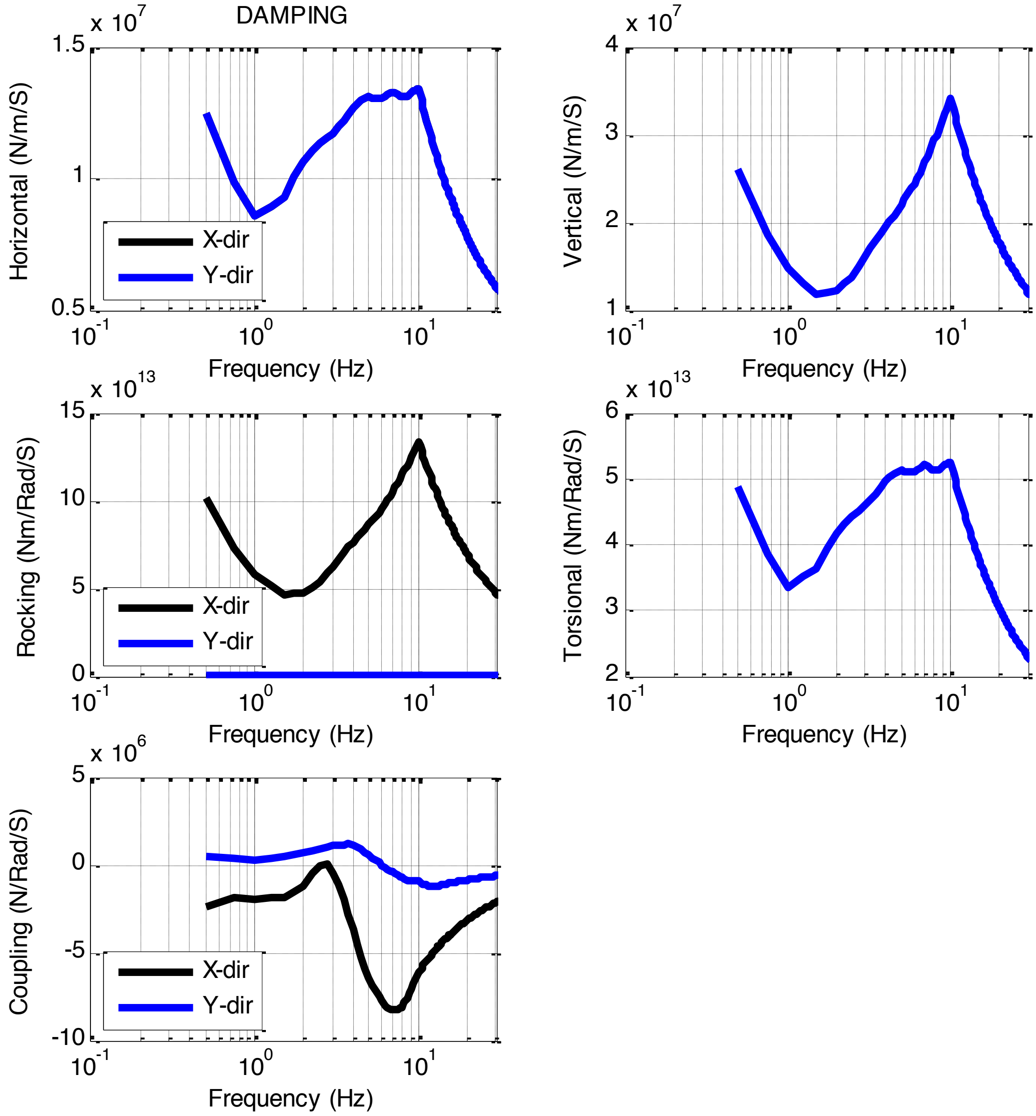


Figure 5.121: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

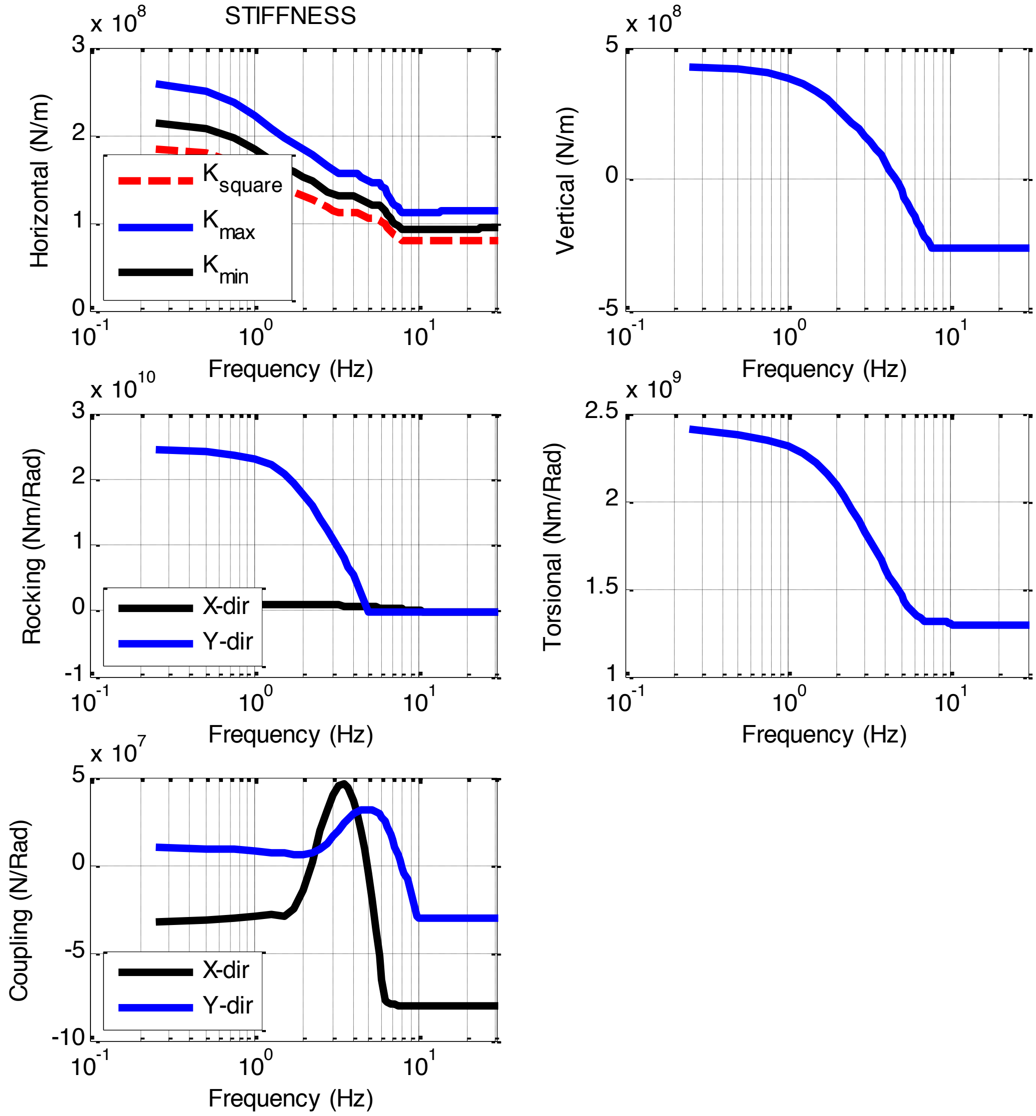


Figure 5.122: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

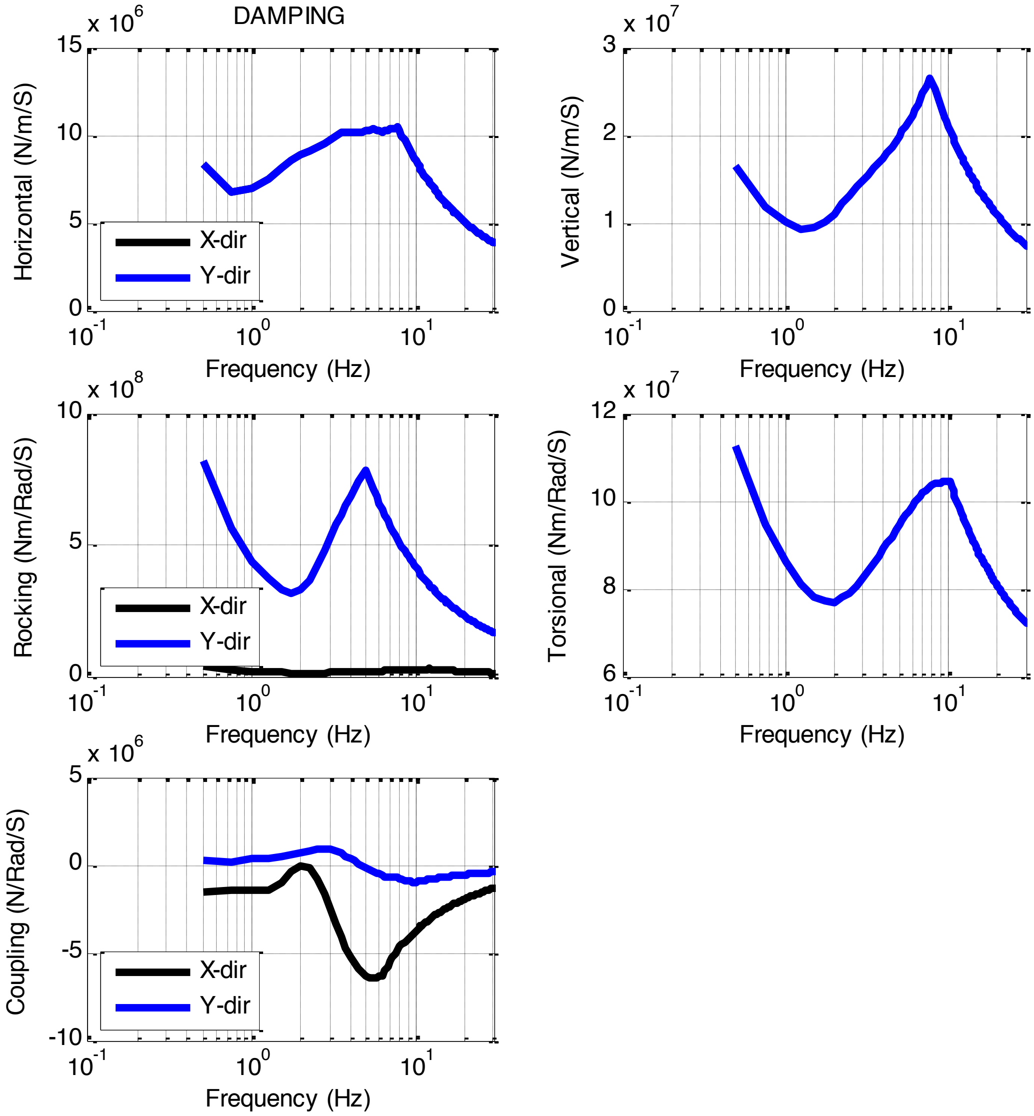


Figure 5.123: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

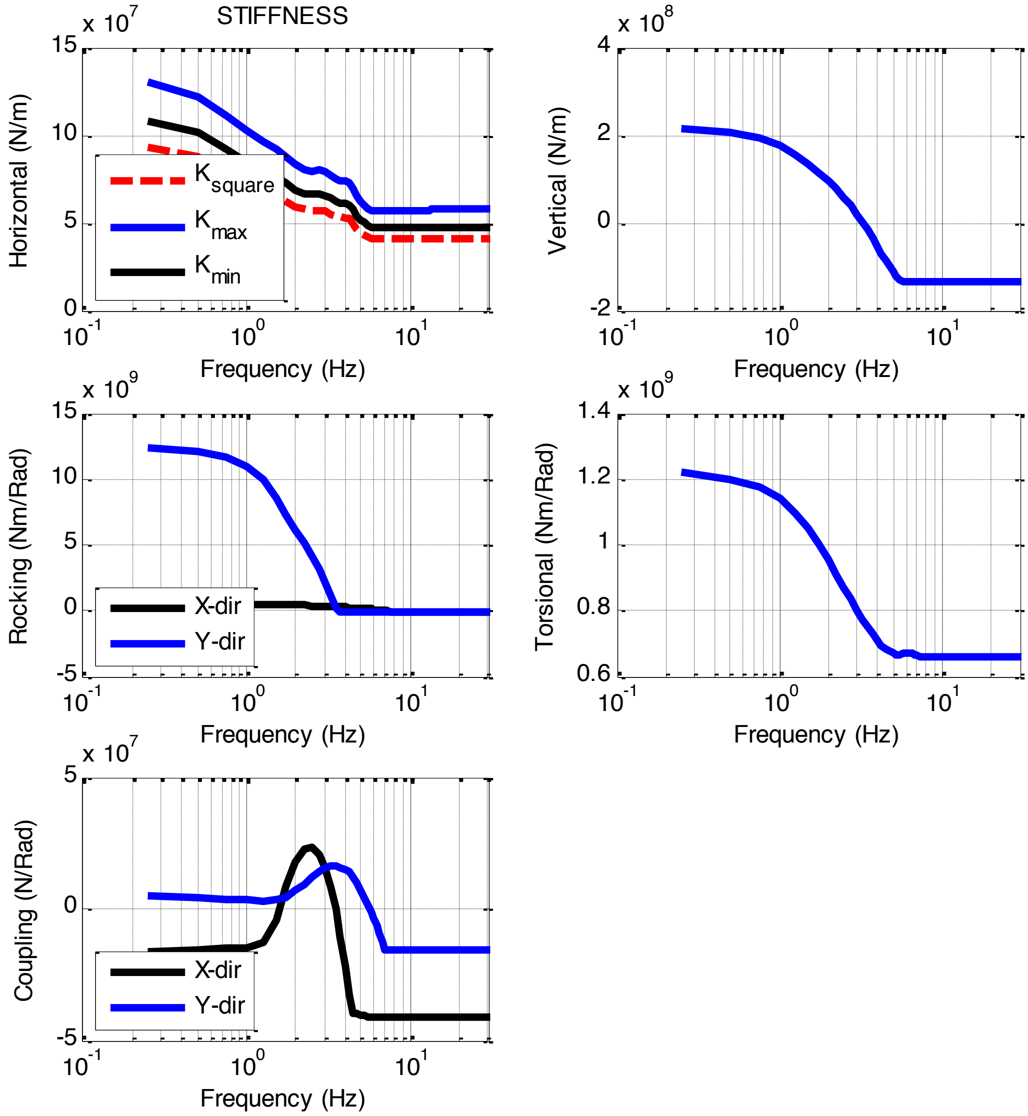


Figure 5.124: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

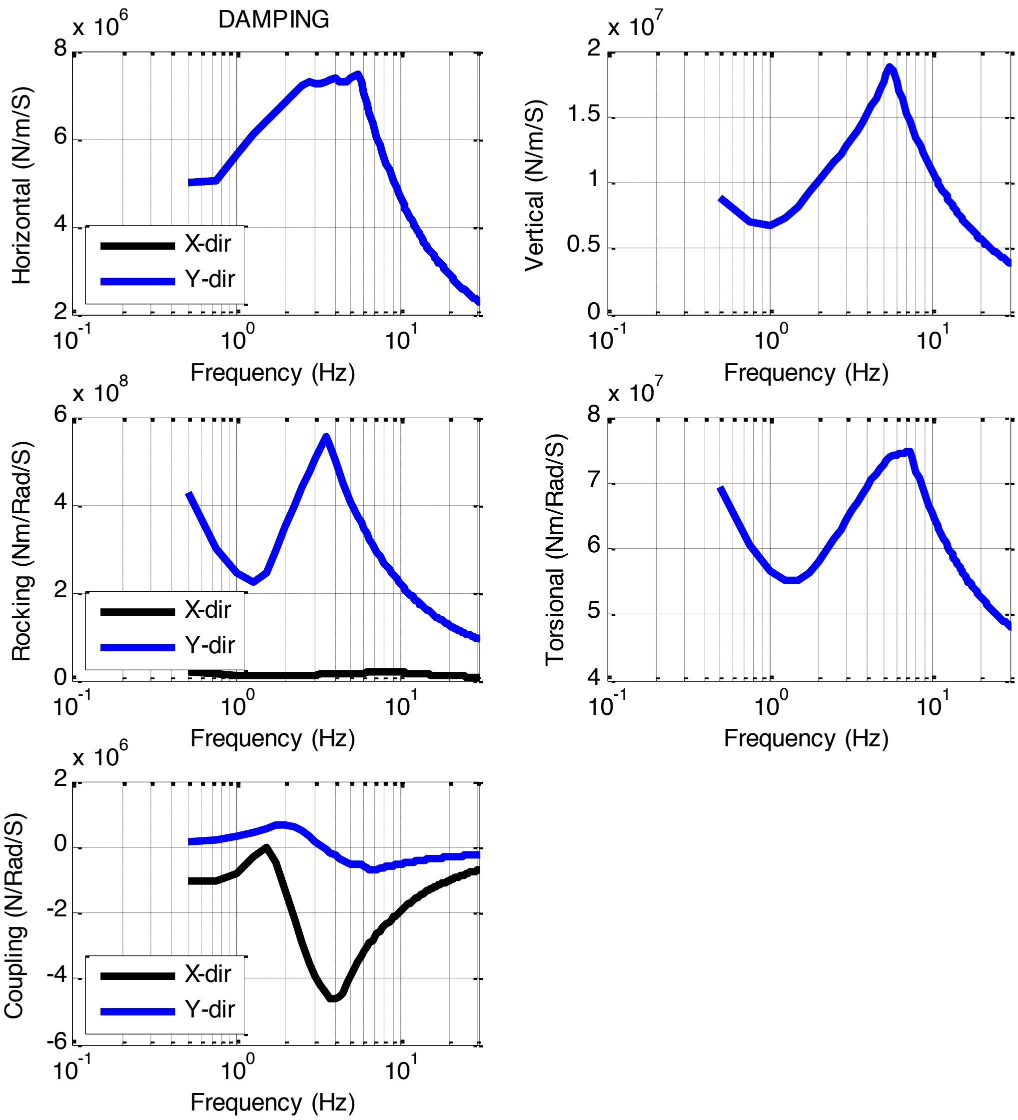


Figure 5.125: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

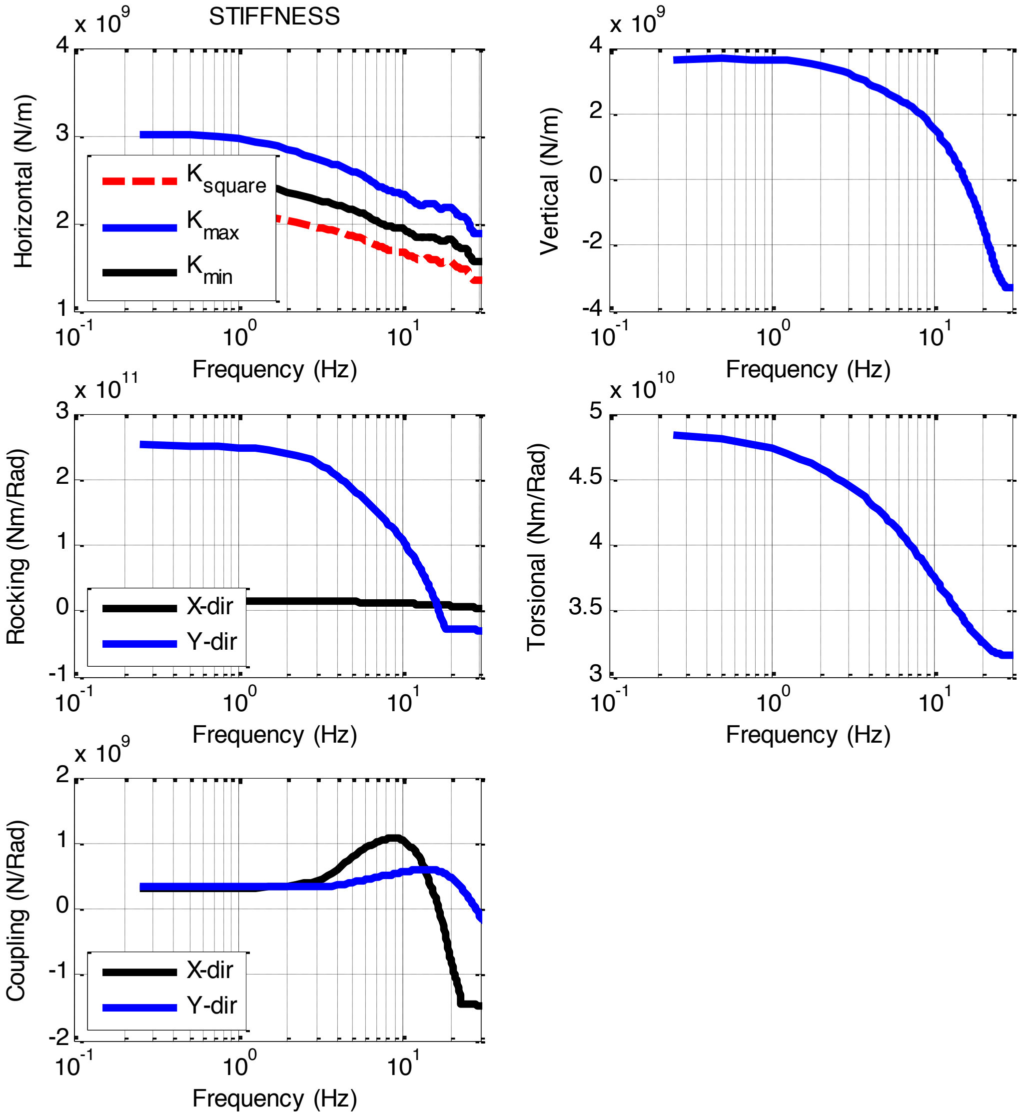


Figure 5.126: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

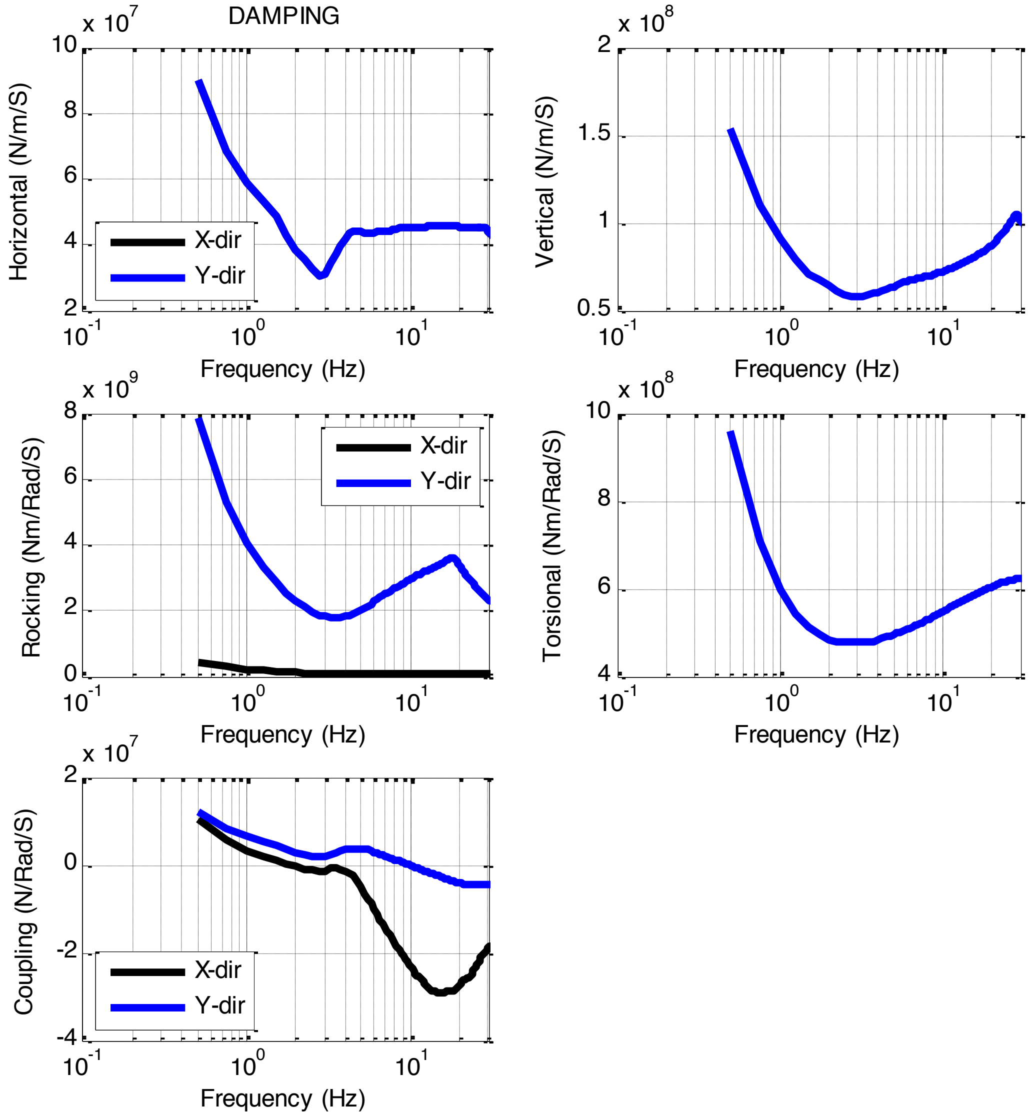


Figure 5.127: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

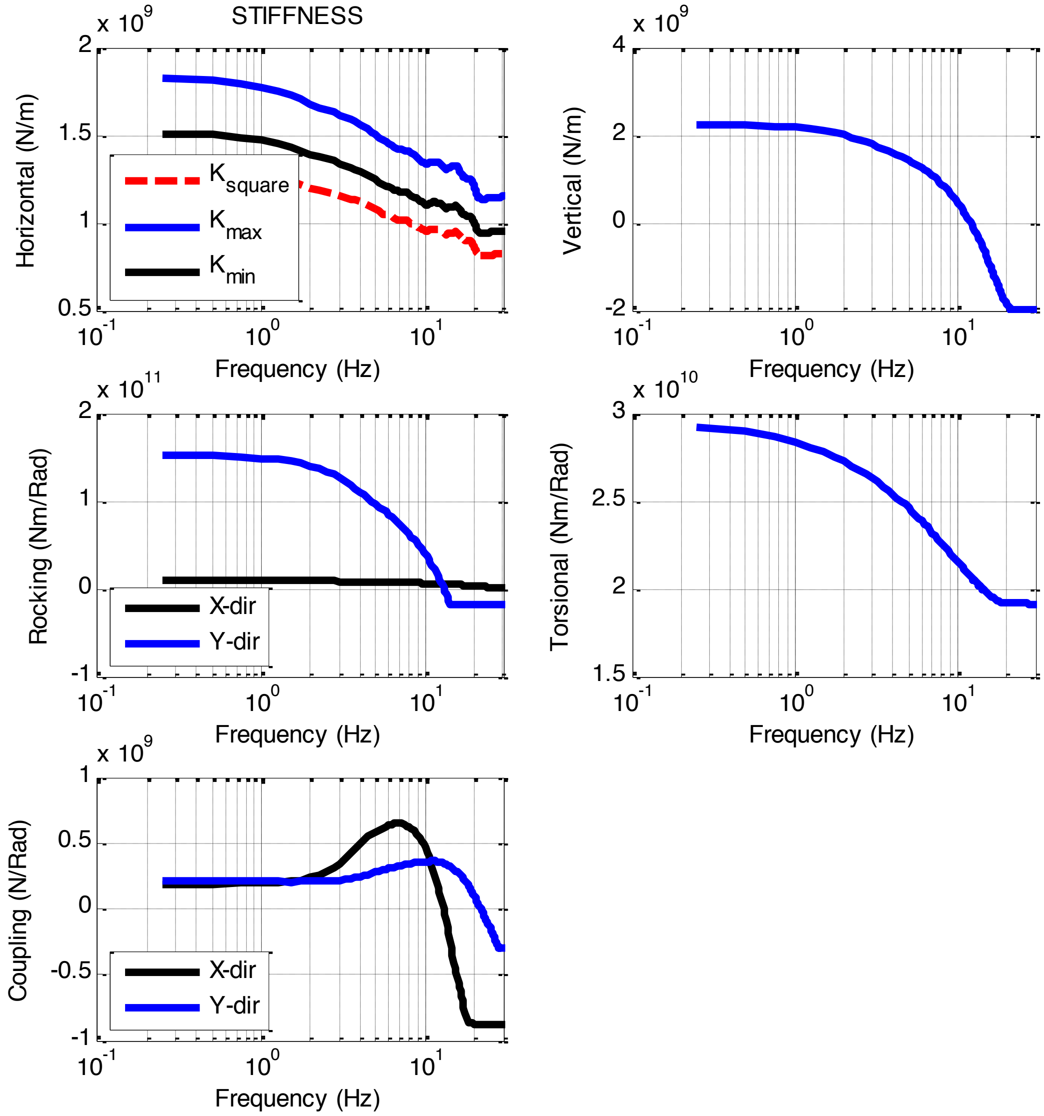


Figure 5.128: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

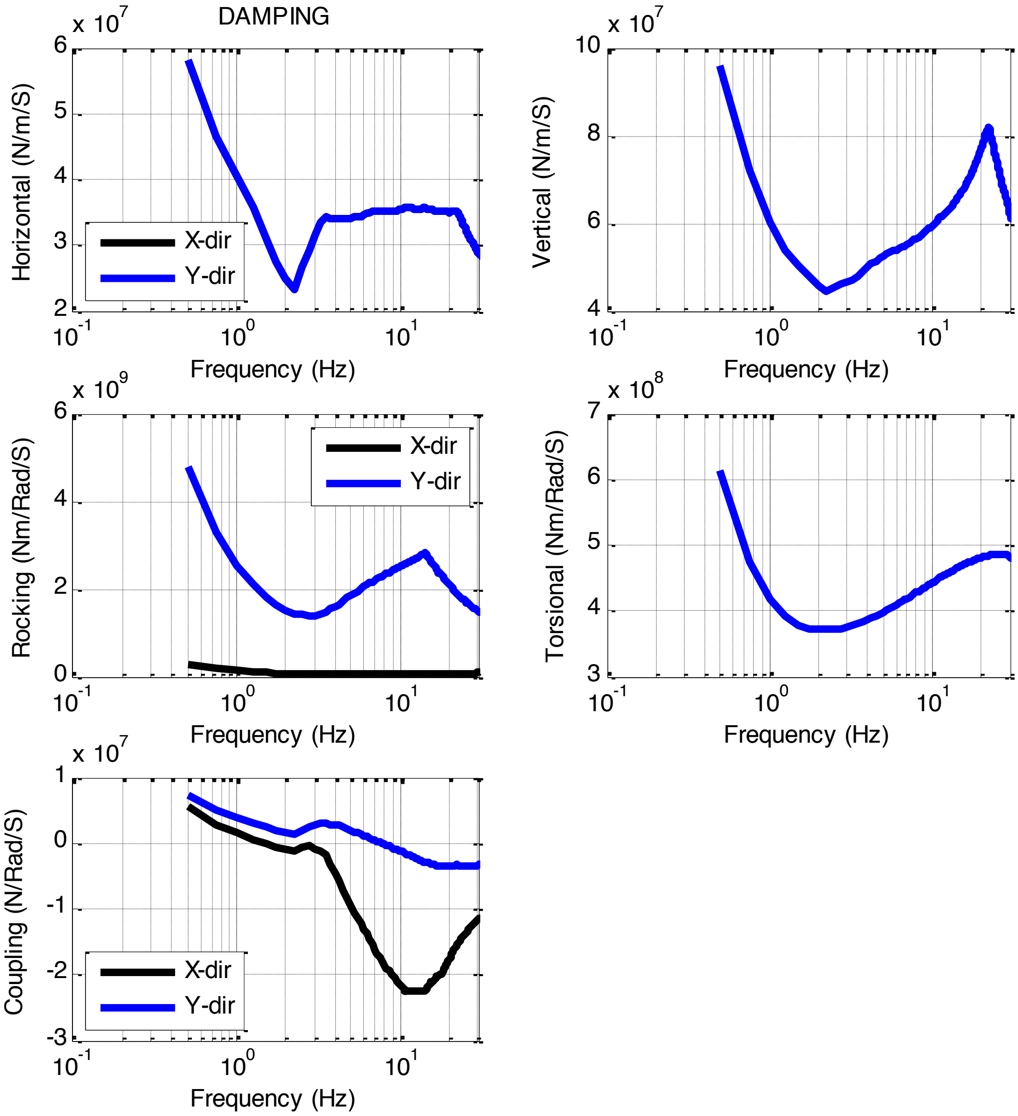


Figure 5.129: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

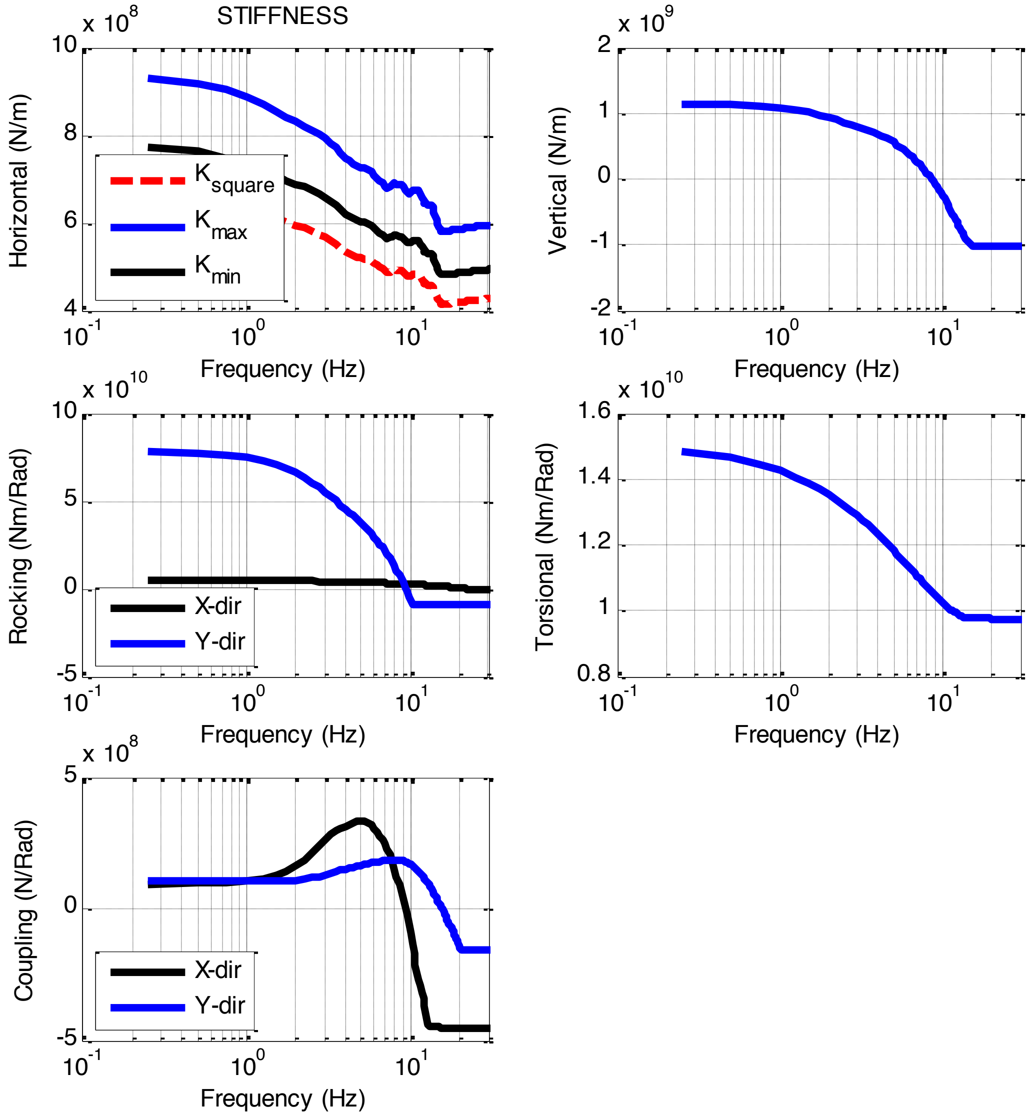


Figure 5.130: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

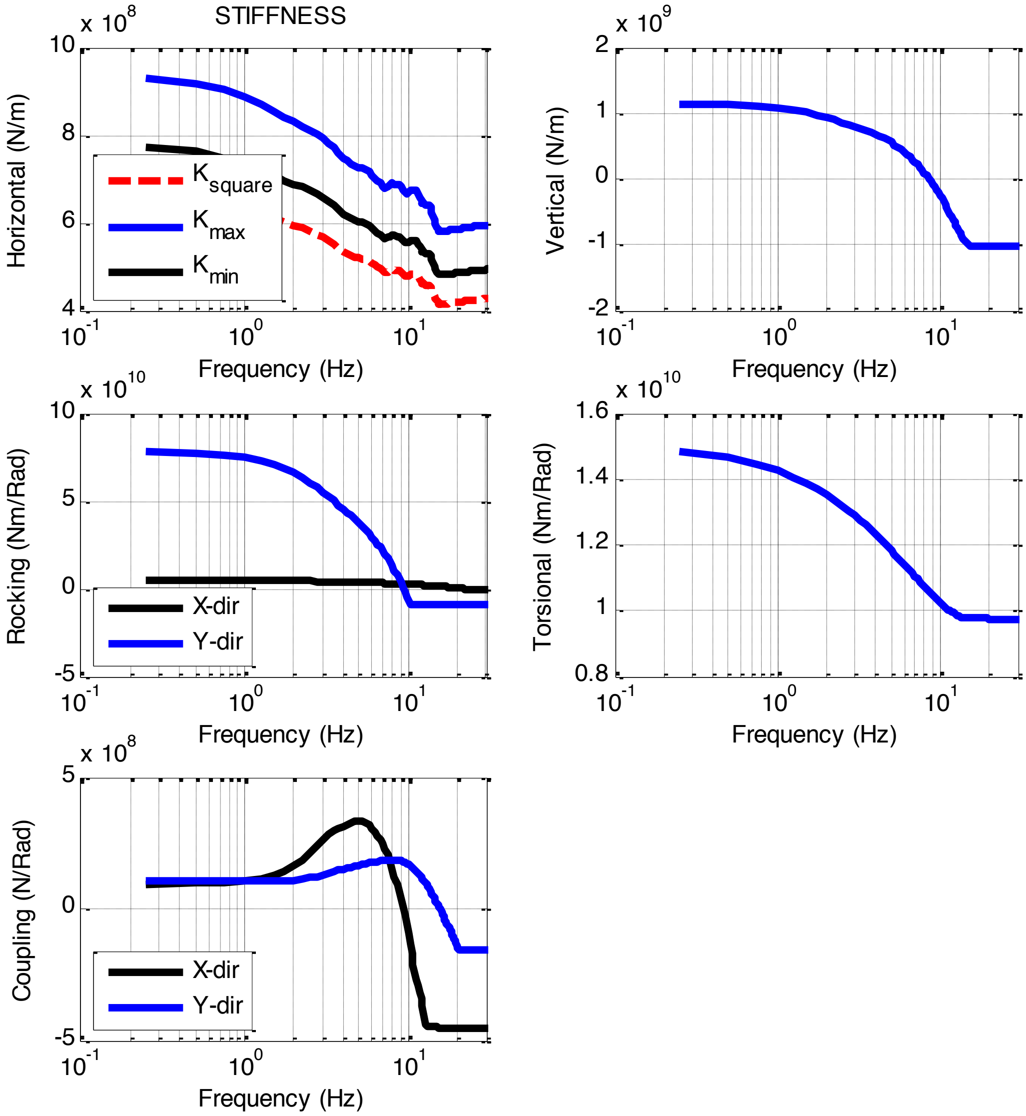


Figure 5.131: Terraced Building with 8 Units on shallow foundations - Concrete foundations – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

6 Impedance functions for buildings on deep foundations

Impedance functions for deep foundations were evaluated considering both fixed and pinned pile head conditions. For the absence of a shallow bedrock level, only floating tip condition is taken into account. A layered soil medium is adopted, the soil model used for deep foundations is described in section 4.1.3.2. Pile-soil-pile interaction is considered. The code requires the following pile properties: dimension, area, inertia, coefficient of rigidity in shear, Young's modulus, Poisson's ratio, damping ratio. The coefficient of rigidity in shear account for the effect of shear on beam vibration, in accordance with the software manual suitable values are equal to 1.11 for a solid circular cross-section and 1.2 for a rectangular cross-section. The effect of shear is significant only for sturdy (rather rigid) piles and rigid bodies, whereas for slender piles this coefficient is not important.

Impedance functions will be calculated considering the following cases:

- 3 building typologies: Detached, Terraced with 4 units and Apartment;
- 1 material type (i.e. concrete);
- 2 representative length (i.e. 16m);
- 2 pile head constraint conditions (i.e. Fixed and pinned);
- 3 reference shear wave velocity profiles (mean; mean – st dev; mean + st dev);
- 3 shear wave velocity scaling factors accounting for different level of non linearity;

For a total number of 54 cases.

6.1 Detached building

Figure 6.1 shows the scheme of the foundations of the Detached building typology. The following sections, for both fixed and pinned head conditions, shows the impedance functions (in terms of frequency dependent stiffness and damping) of the building taking into account the three reference soil profiles defined in section 4.1.1 and the three scaling factors of section 4.1.2. The characteristics of the cap foundations are summarized in the following table. The foundation consists of 250x250 mm square section concrete piles ($A=0.0625m^2$; $I_{xx}=I_{yy}=0.0003255m^4$; $I_{zz}=0.0006510m^4$). The pile length considered is equal to 16m.

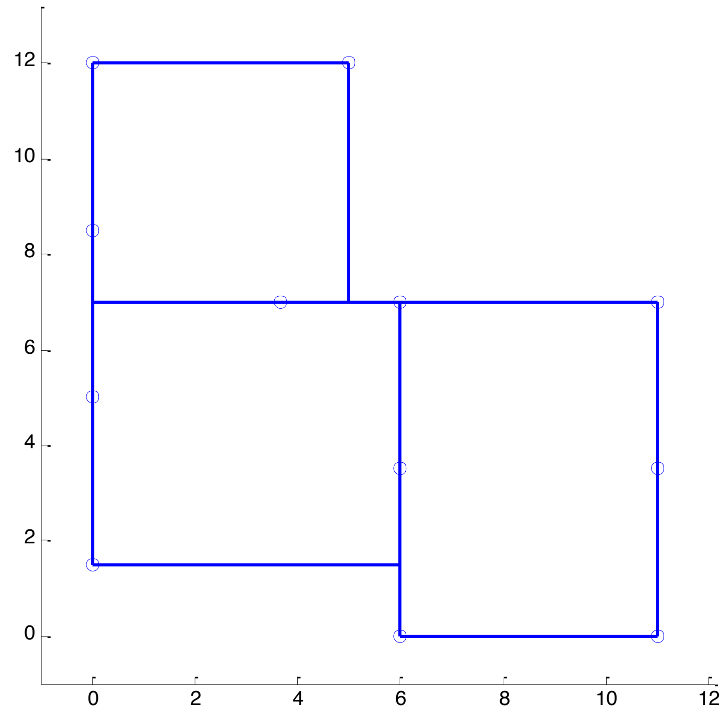


Figure 6.1: Detached building: schematic position of beam foundations and location of piles

Table 6.1: Foundations characteristics of Detached building

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m²]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m²]	I_{yy} [kg m²]	I_{zz} [kg m²]	I_{xy} [kg m²]	I_{xz} [kg m²]	I_{yz} [kg m²]
11	12	0.45	17.0	3.94	4.30	19.1e3	270.3e3	267.0e3	536.7e3	-96.1e3	0	0

6.1.1 Fixed head conditions

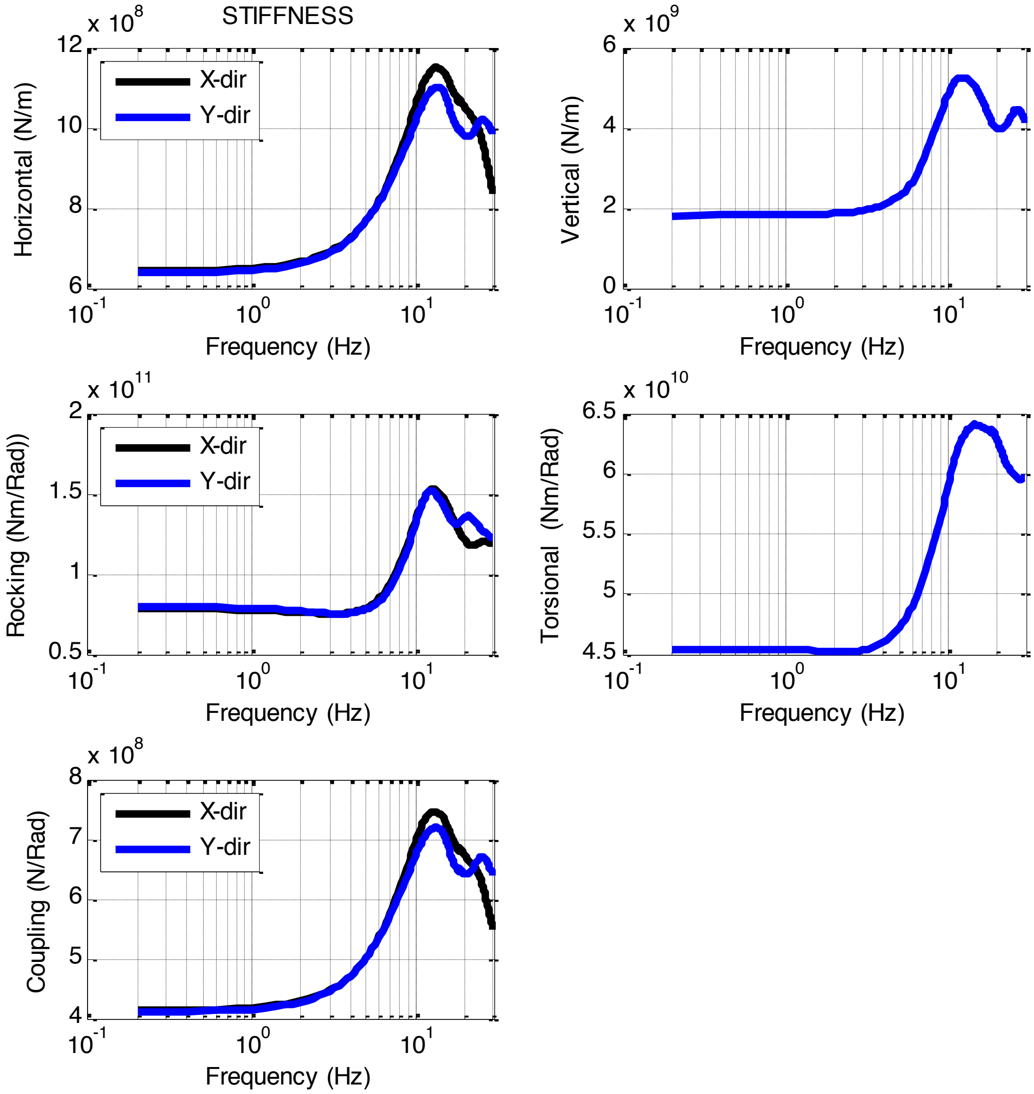


Figure 6.2: Detached Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF1: STIFFNESS

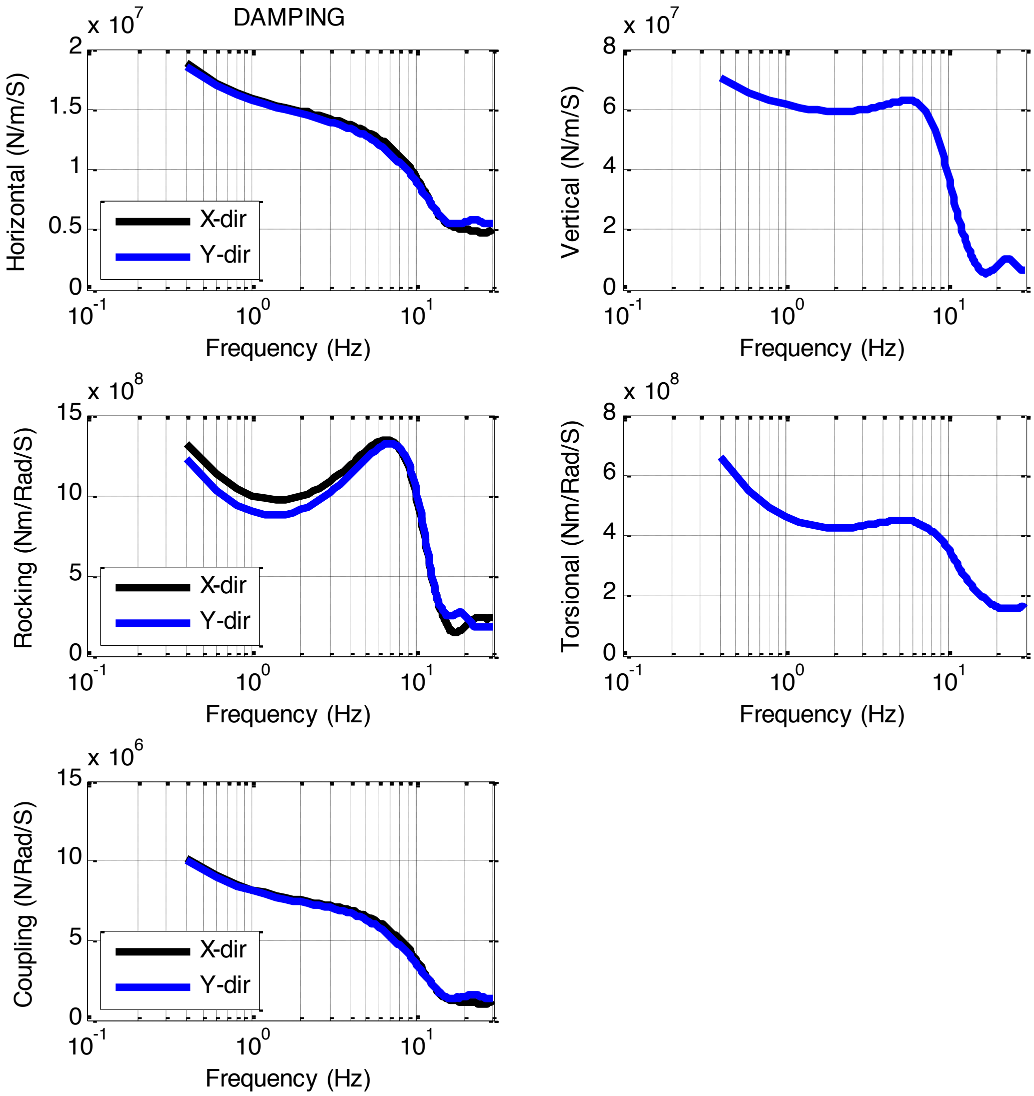


Figure 6.3: Detached Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF1: DAMPING

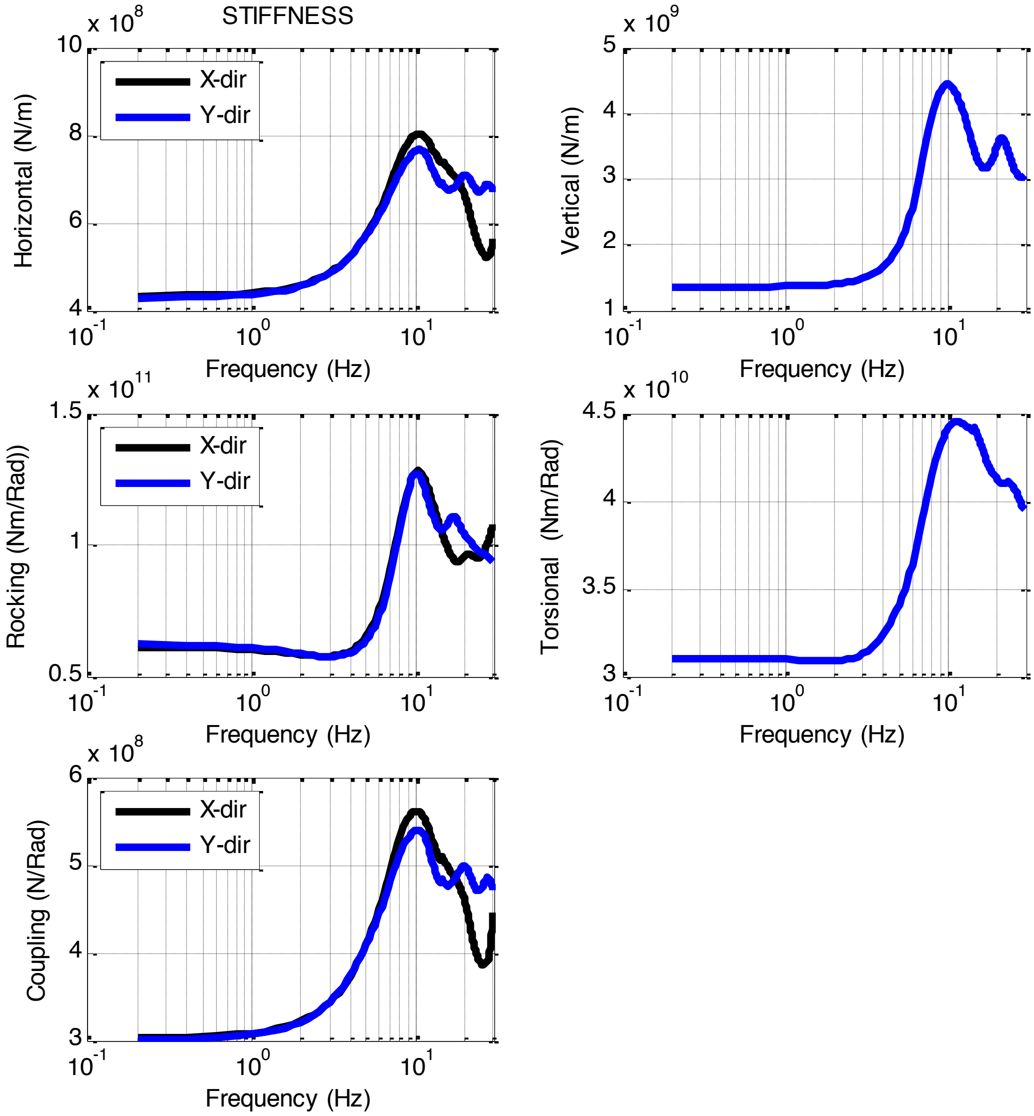


Figure 6.4: Detached Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF2: STIFFNESS

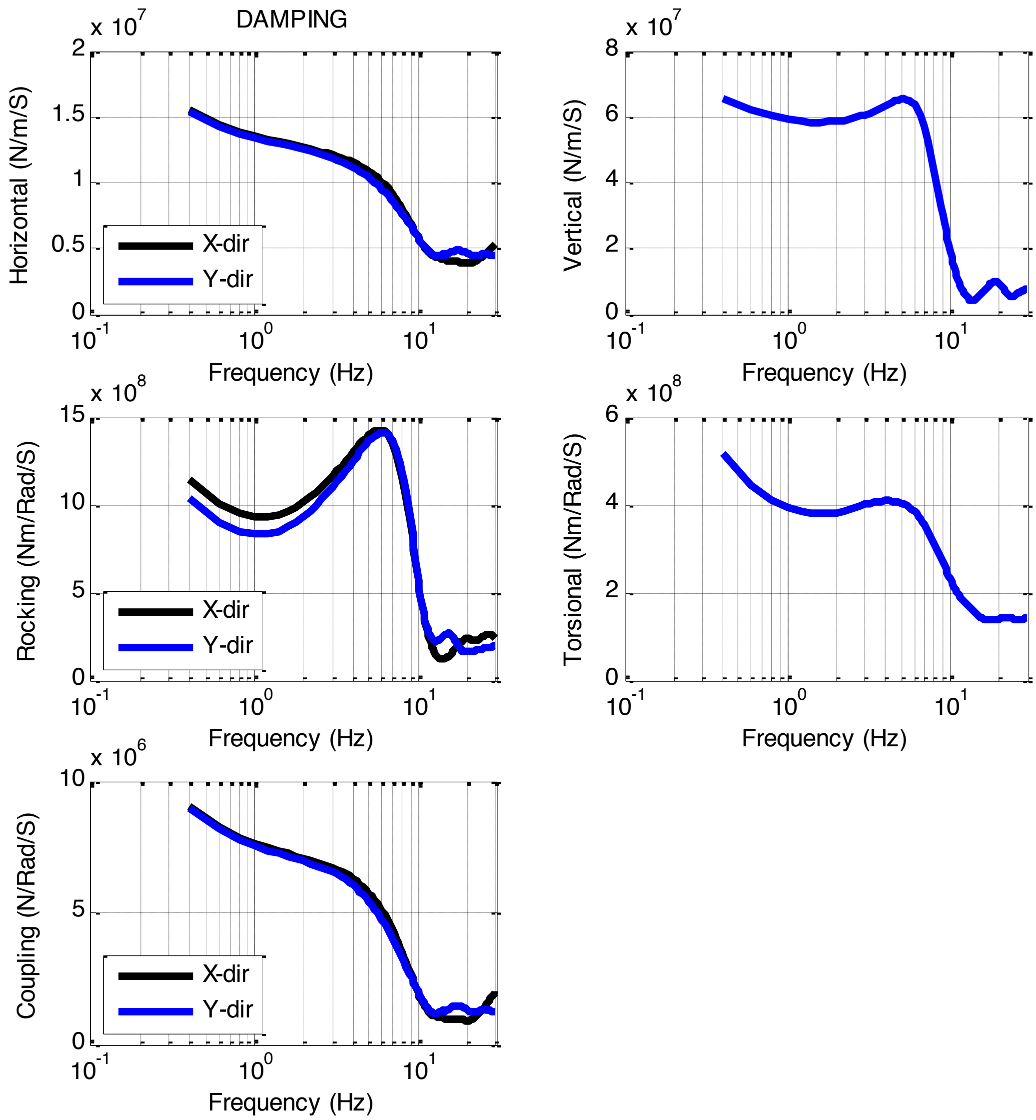


Figure 6.5: Detached Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF2: DAMPING

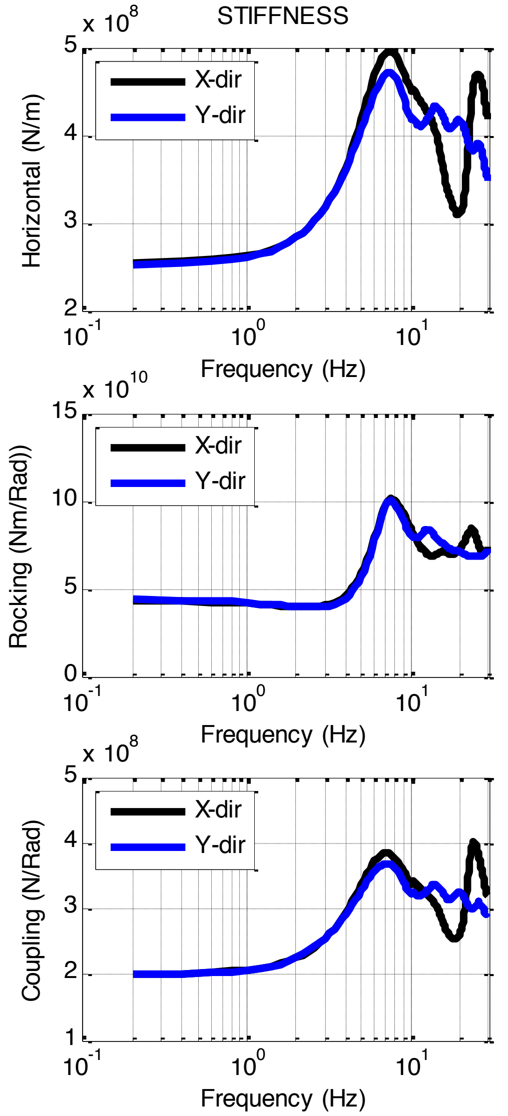


Figure 6.6: Detached Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF3: STIFFNESS

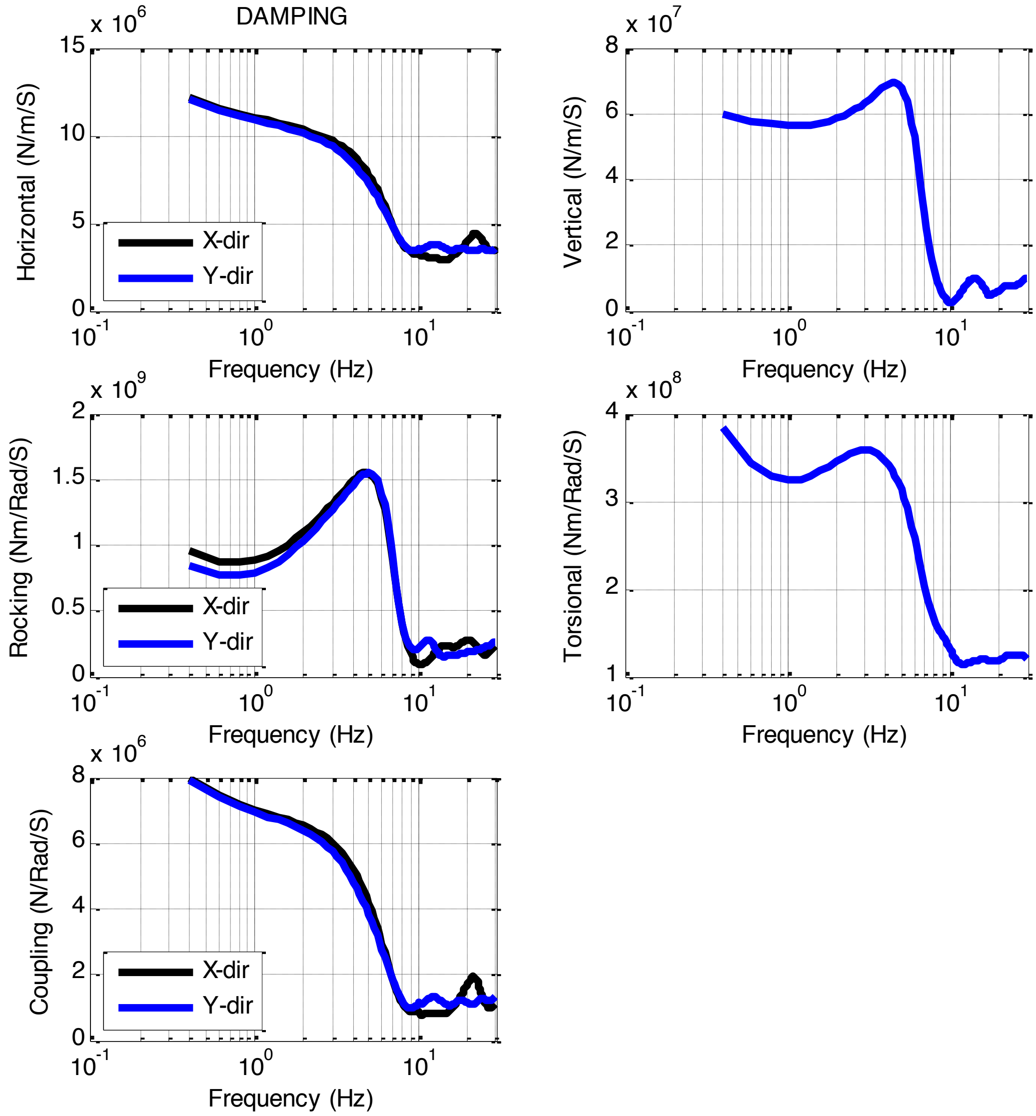


Figure 6.7: Detached Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF3: DAMPING

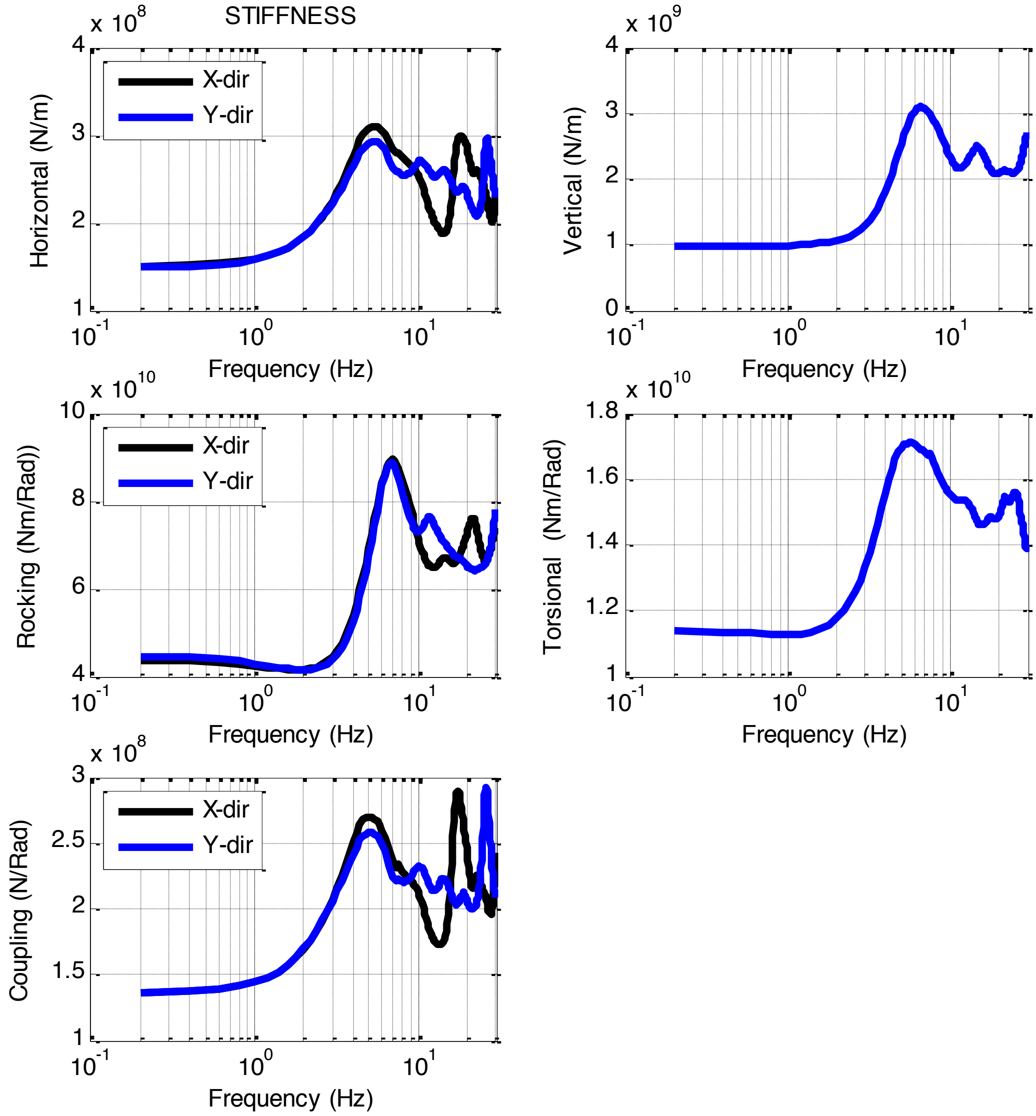


Figure 6.8: Detached Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

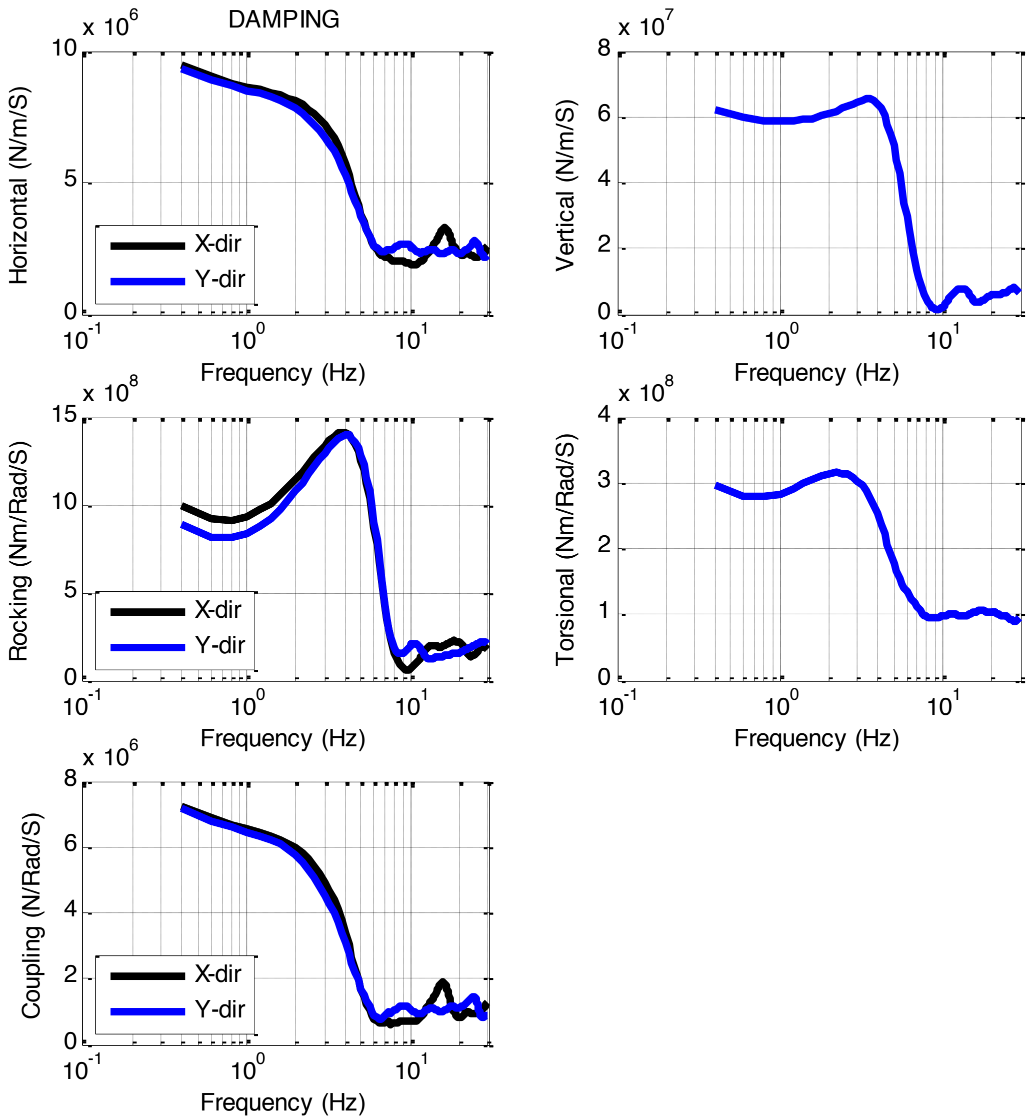


Figure 6.9: Detached Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

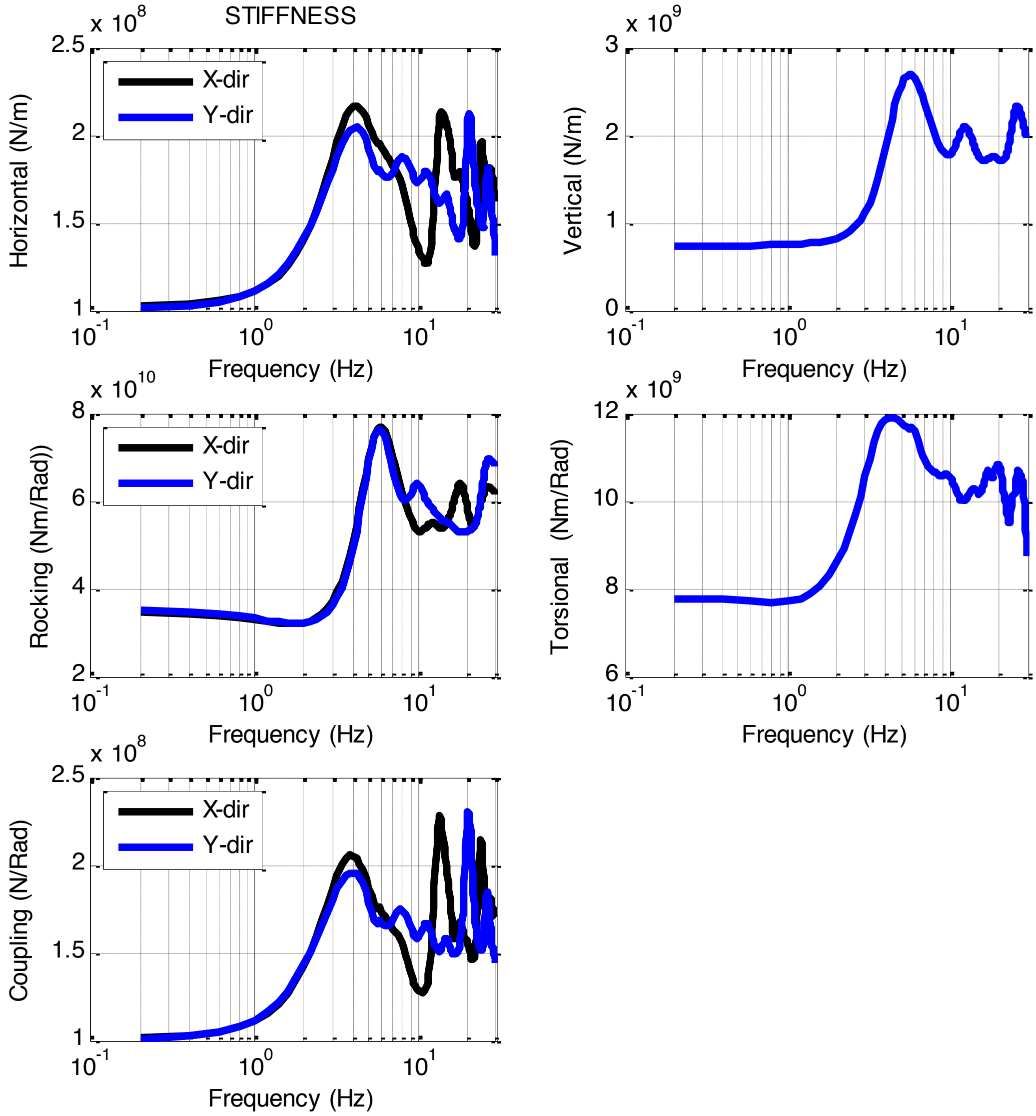


Figure 6.10: Detached Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

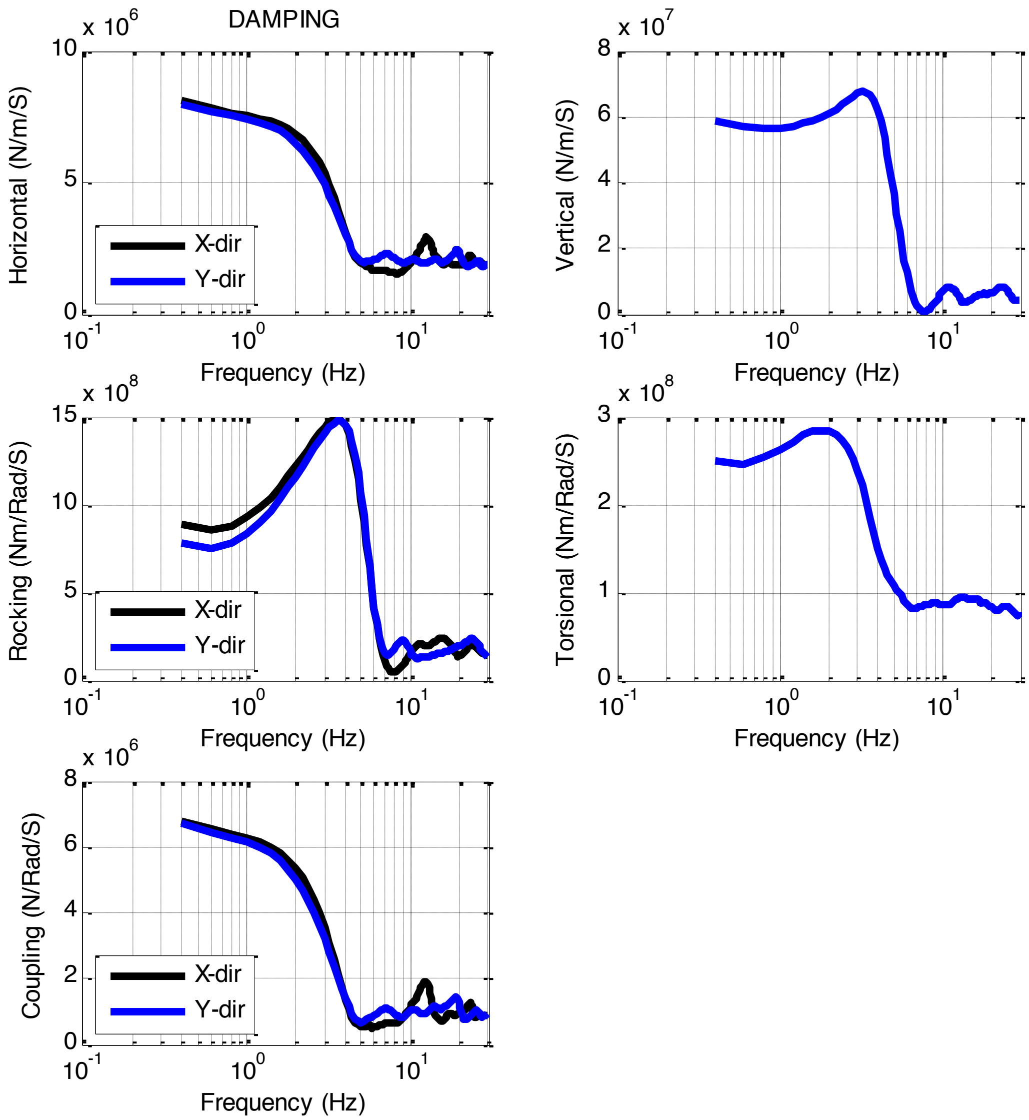


Figure 6.11: Detached Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

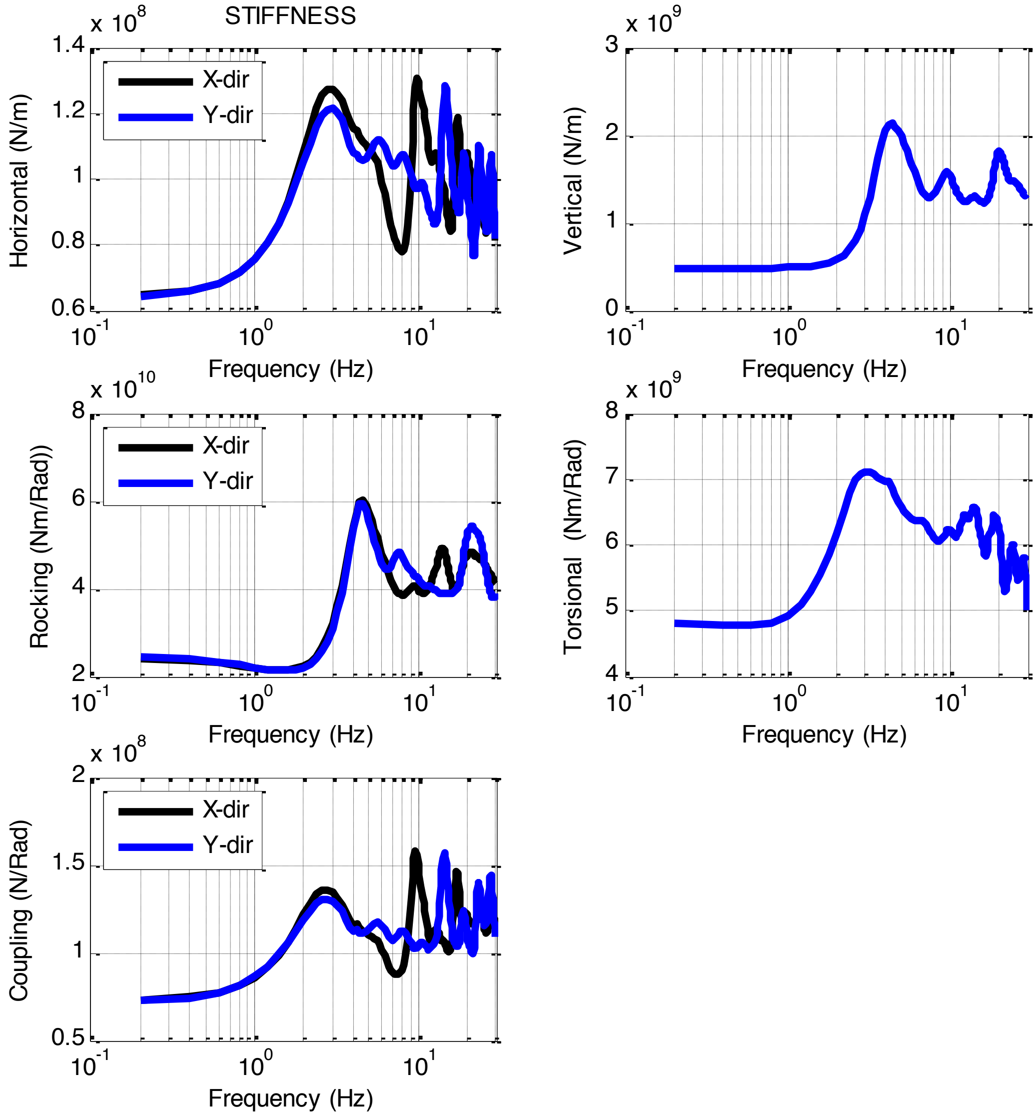


Figure 6.12: Detached Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

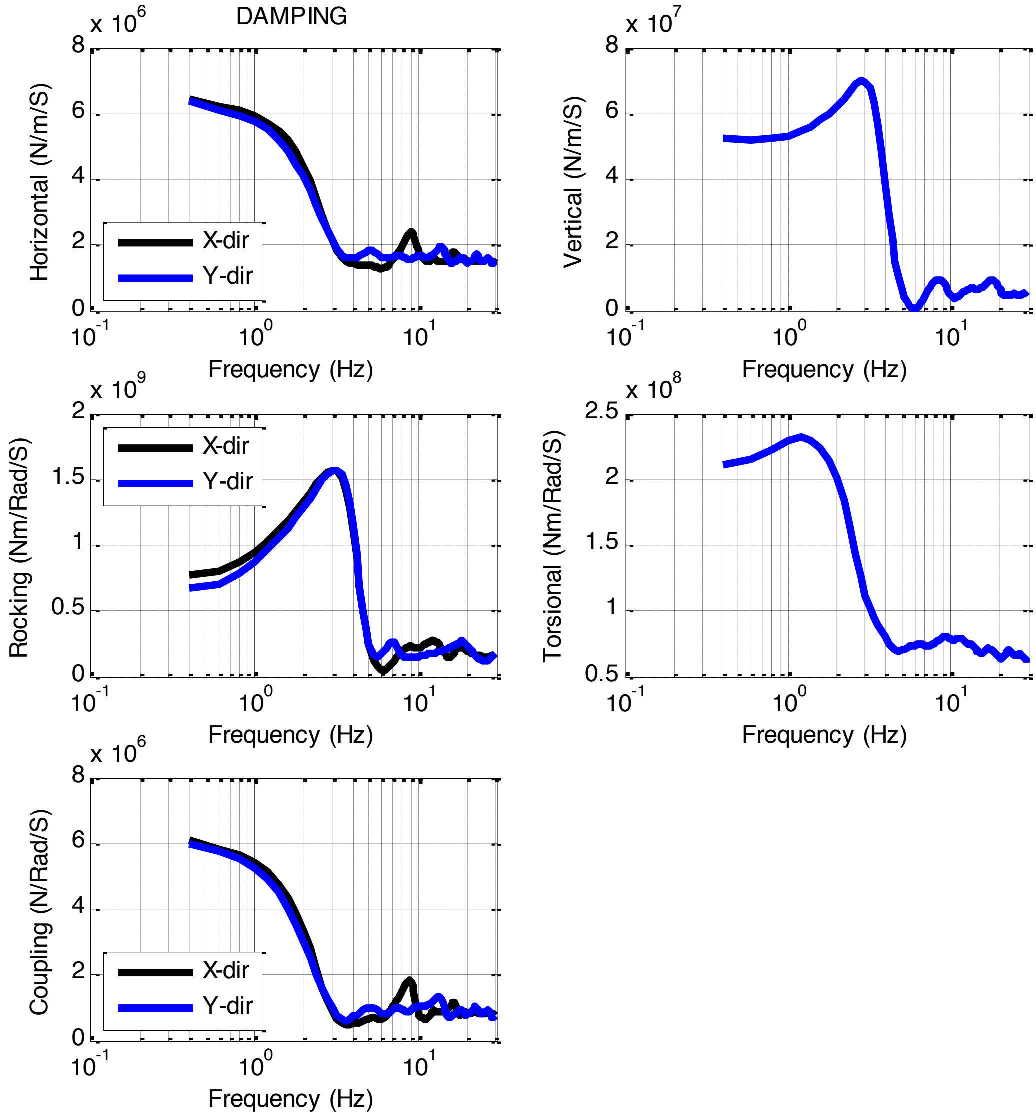


Figure 6.13: Detached Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

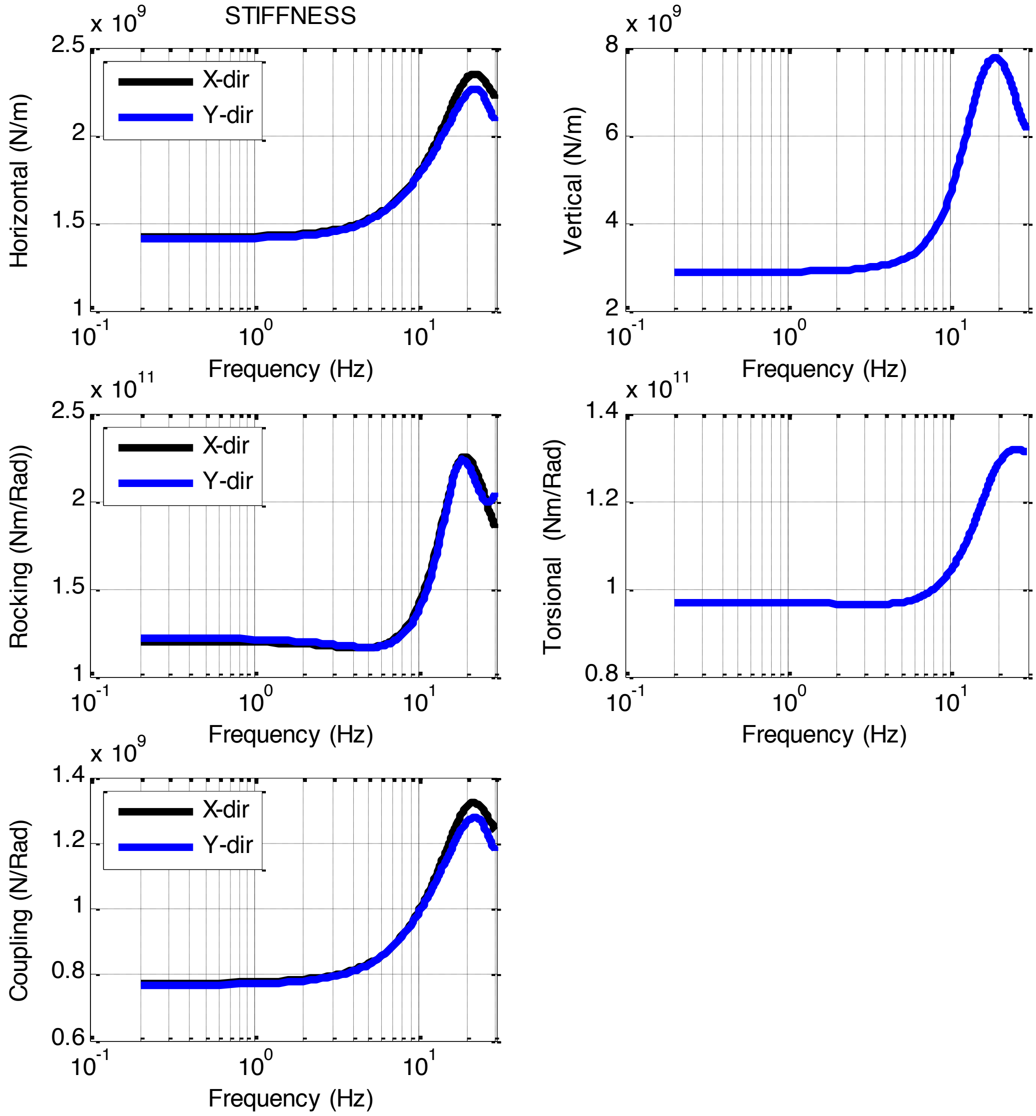


Figure 6.14: Detached Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

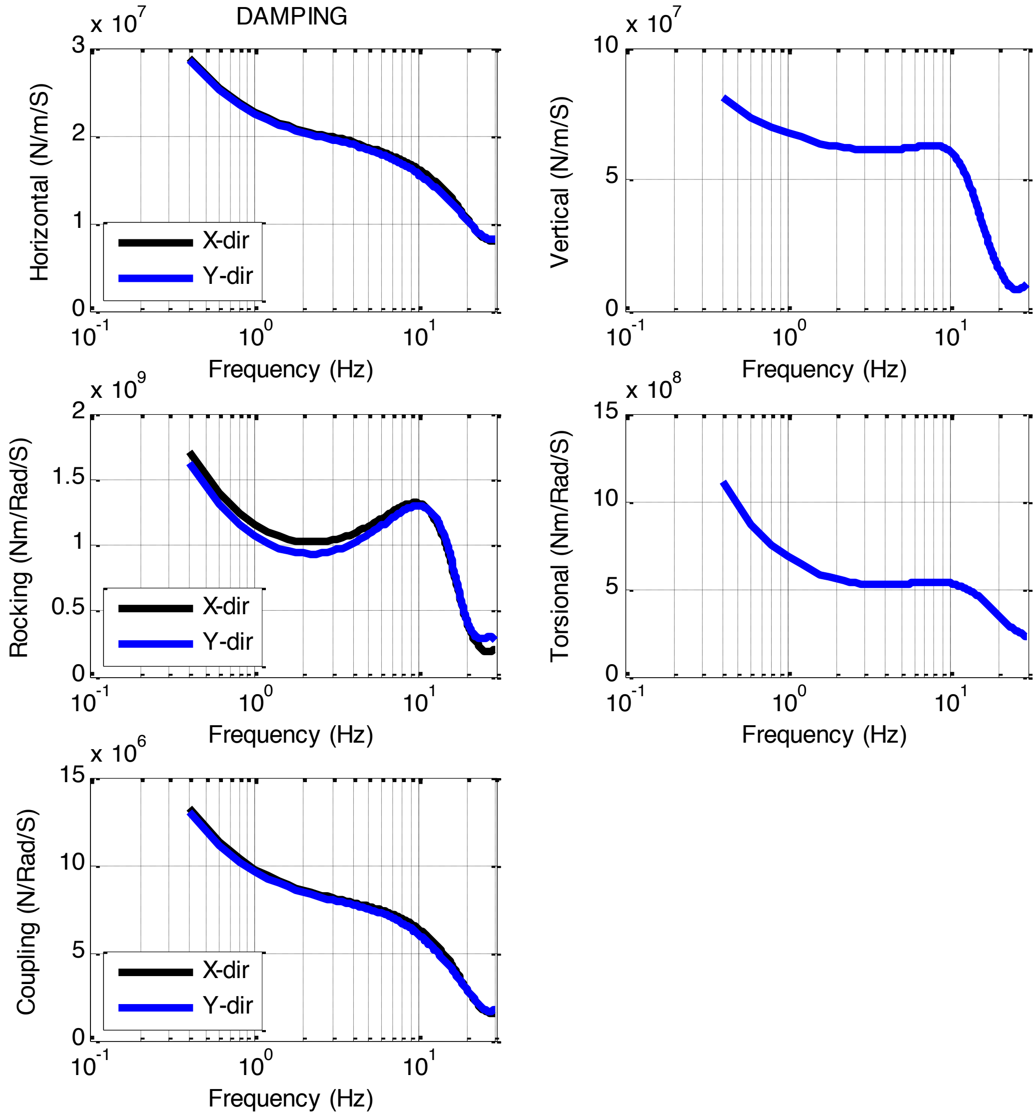


Figure 6.15: Detached Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

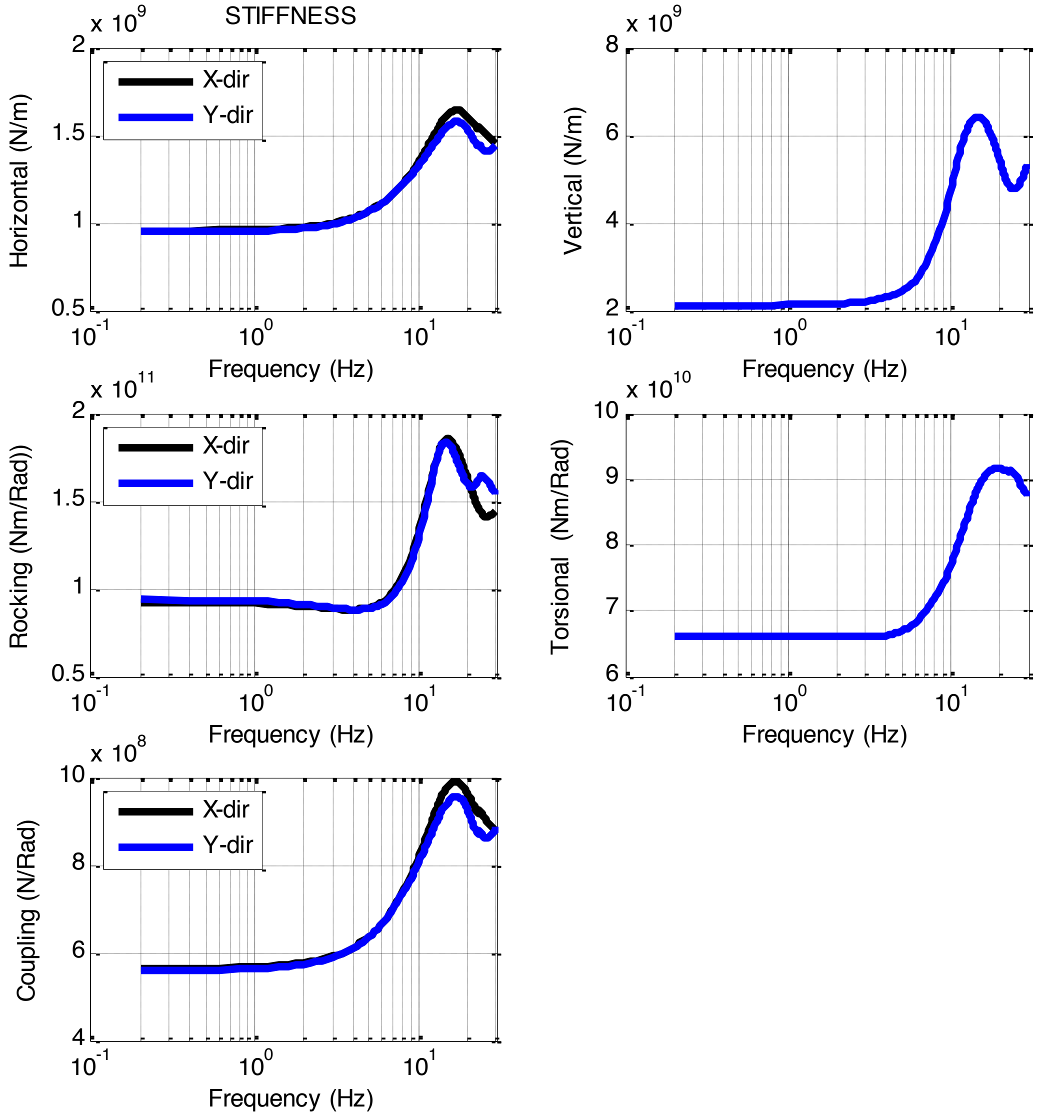


Figure 6.16: Detached Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

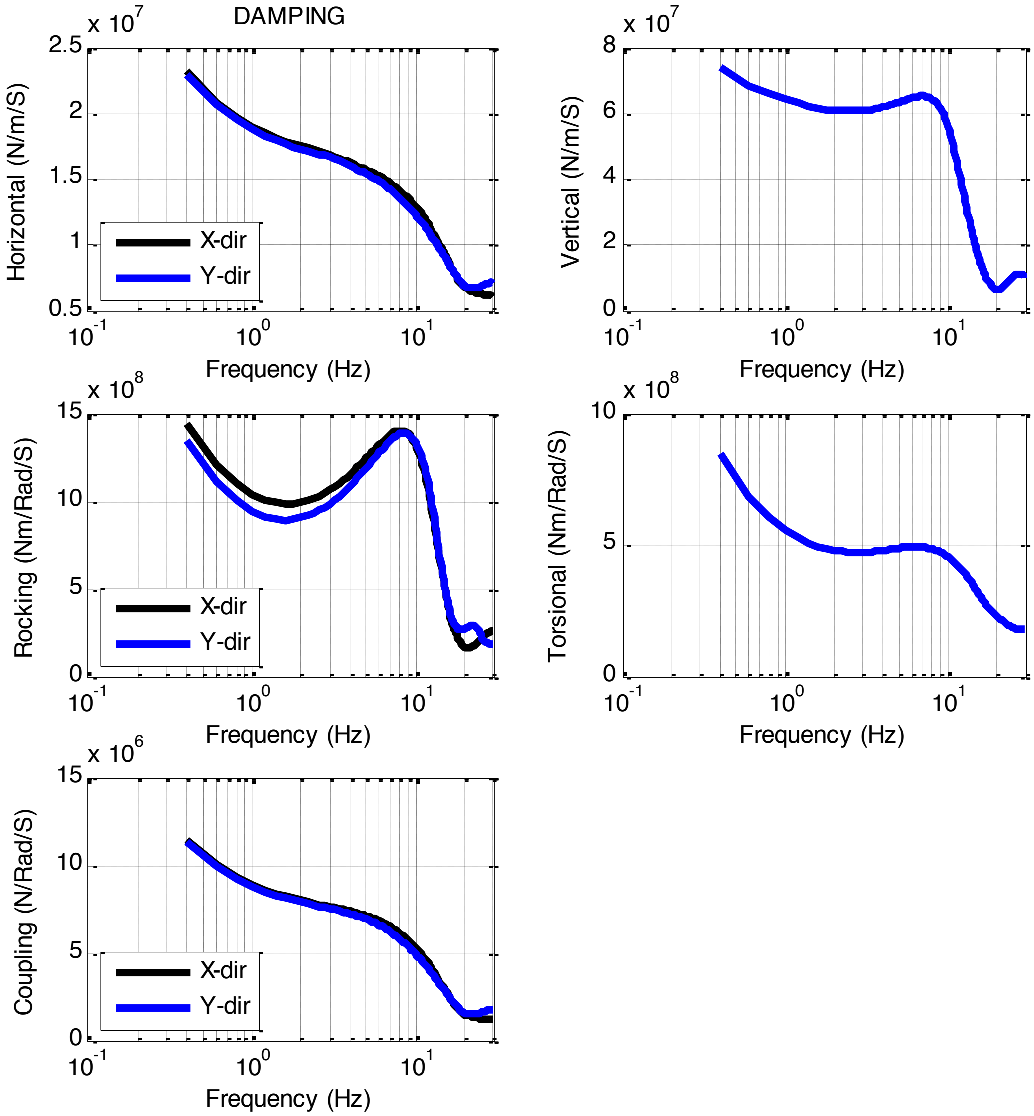


Figure 6.17: Detached Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

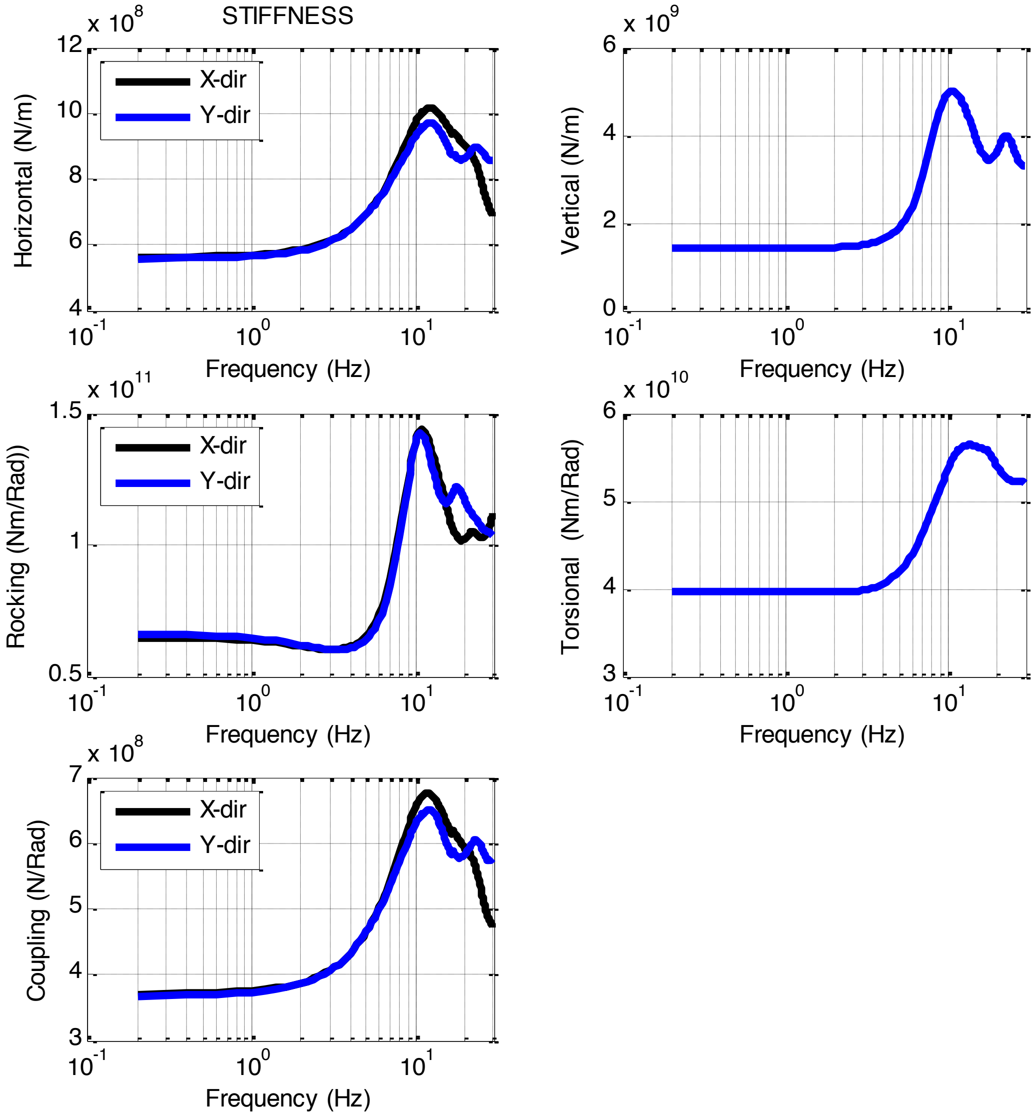


Figure 6.18: Detached Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

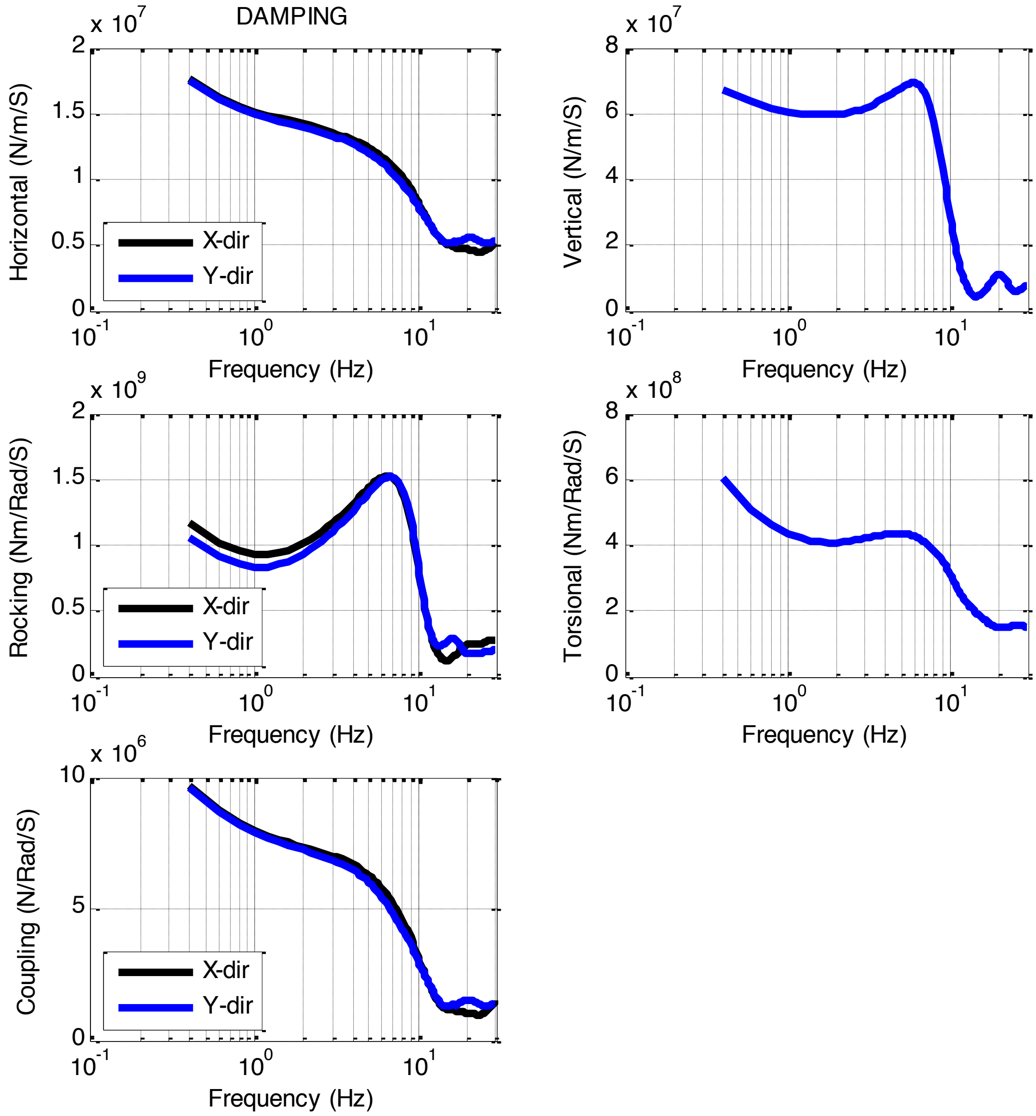


Figure 6.19: Detached Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

6.1.2 Pinned head conditions

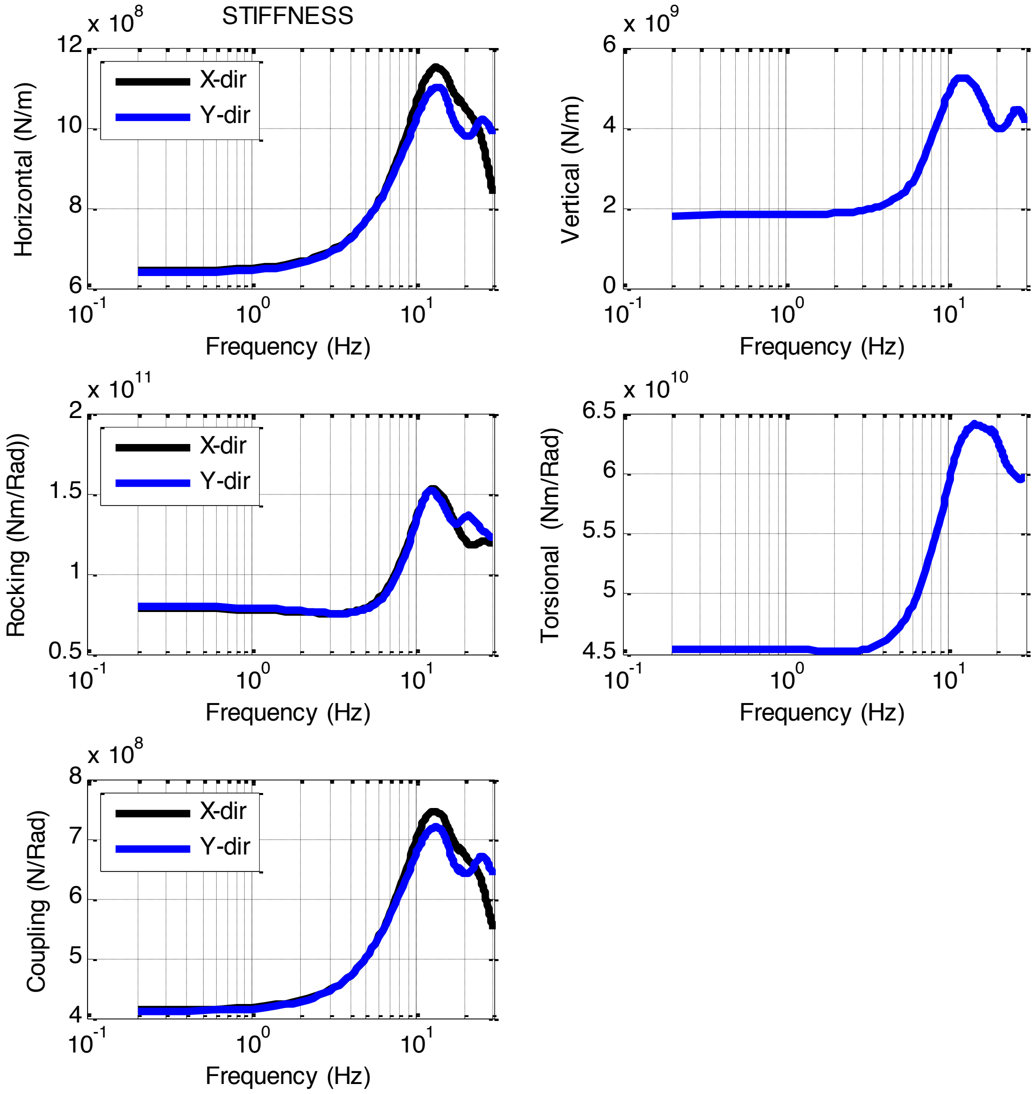


Figure 6.20: Detached Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF1: STIFFNESS

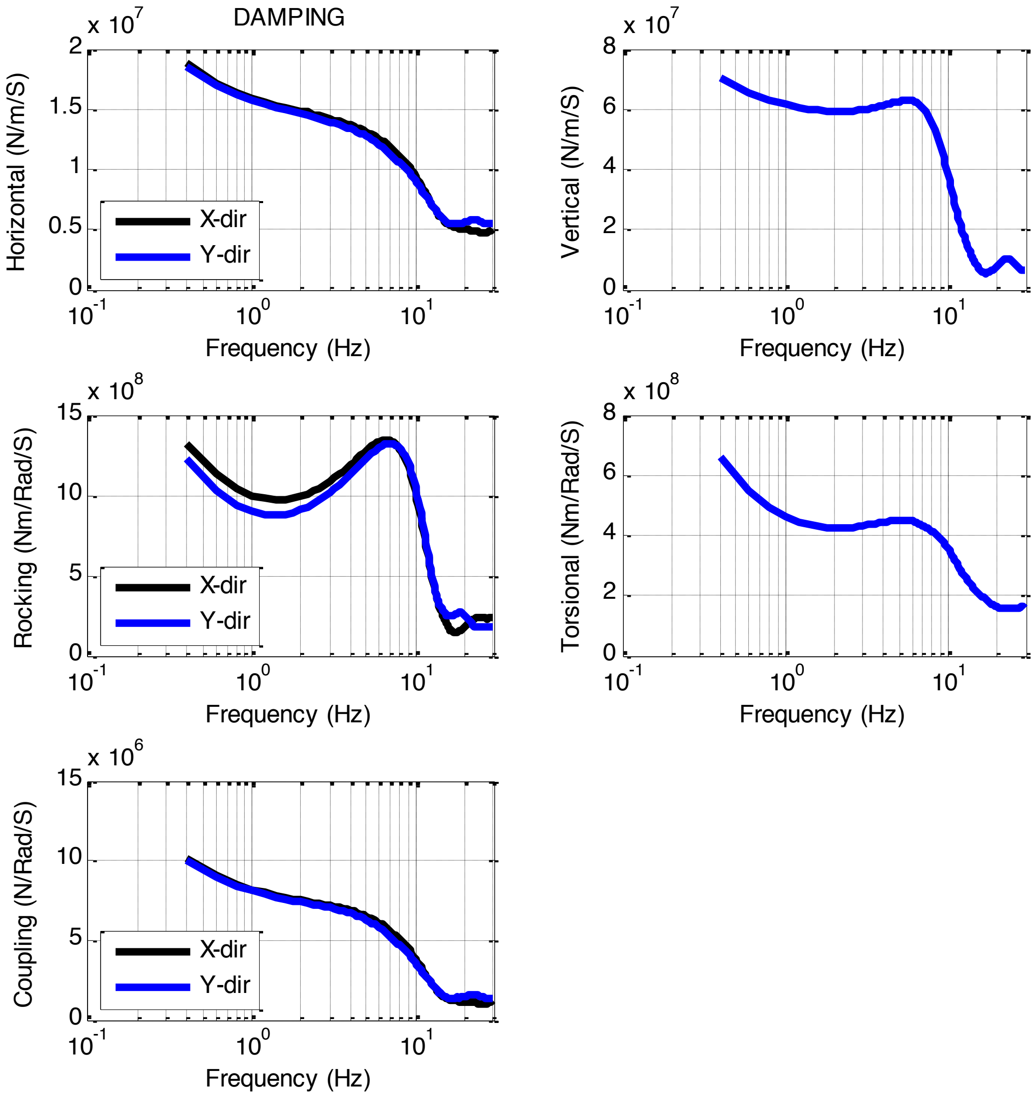


Figure 6.21: Detached Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF1: DAMPING

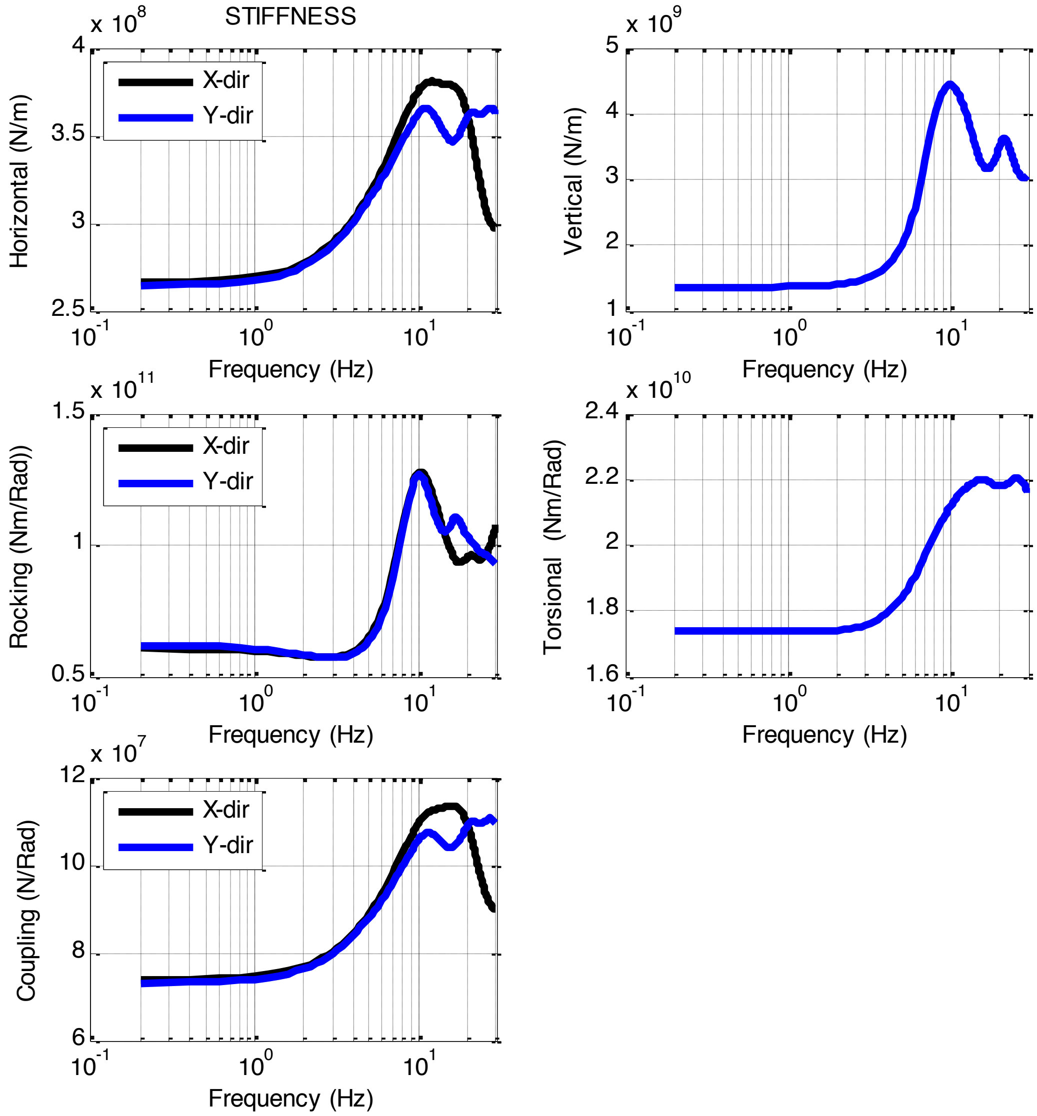


Figure 6.22: Detached Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF2: STIFFNESS

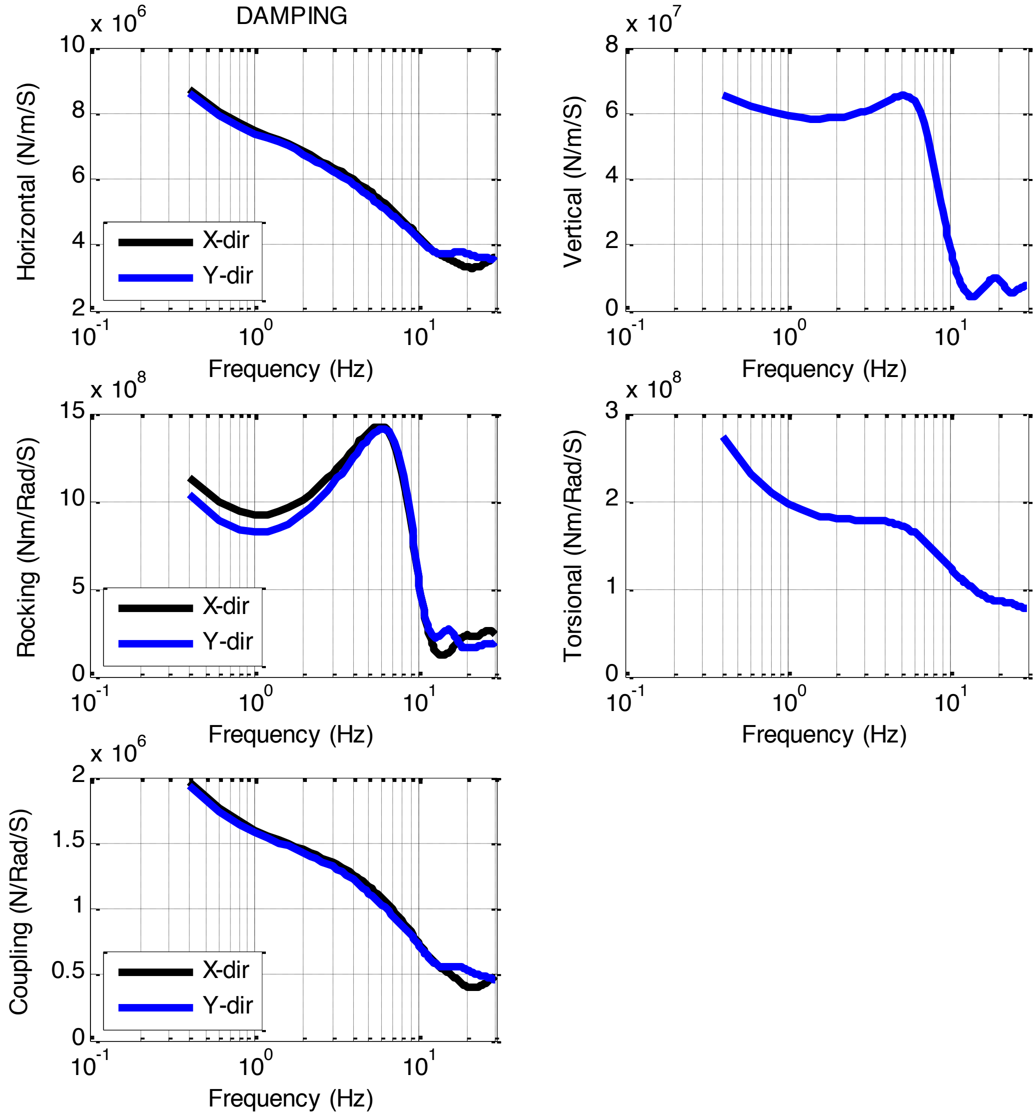


Figure 6.23: Detached Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF2: DAMPING

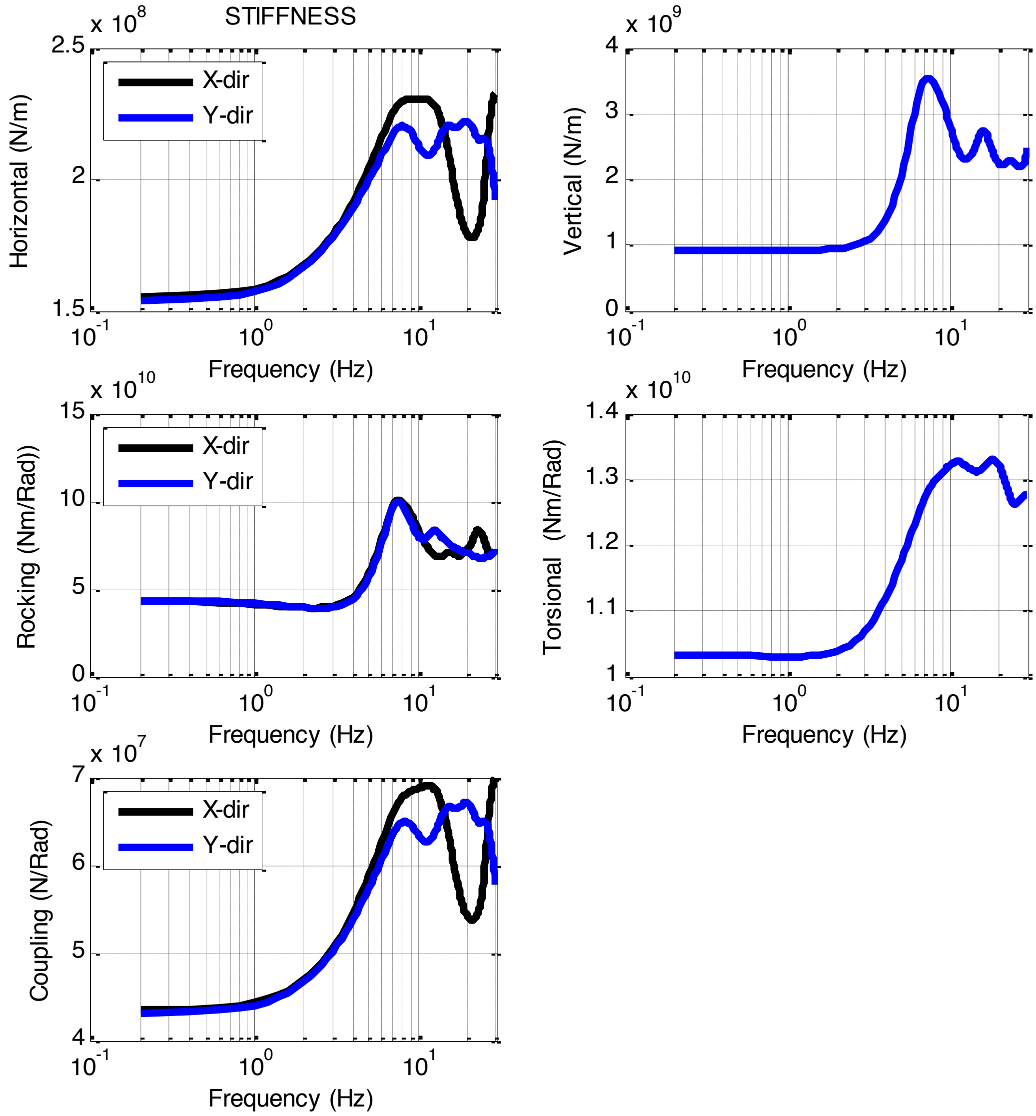


Figure 6.24: Detached Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF3: STIFFNESS

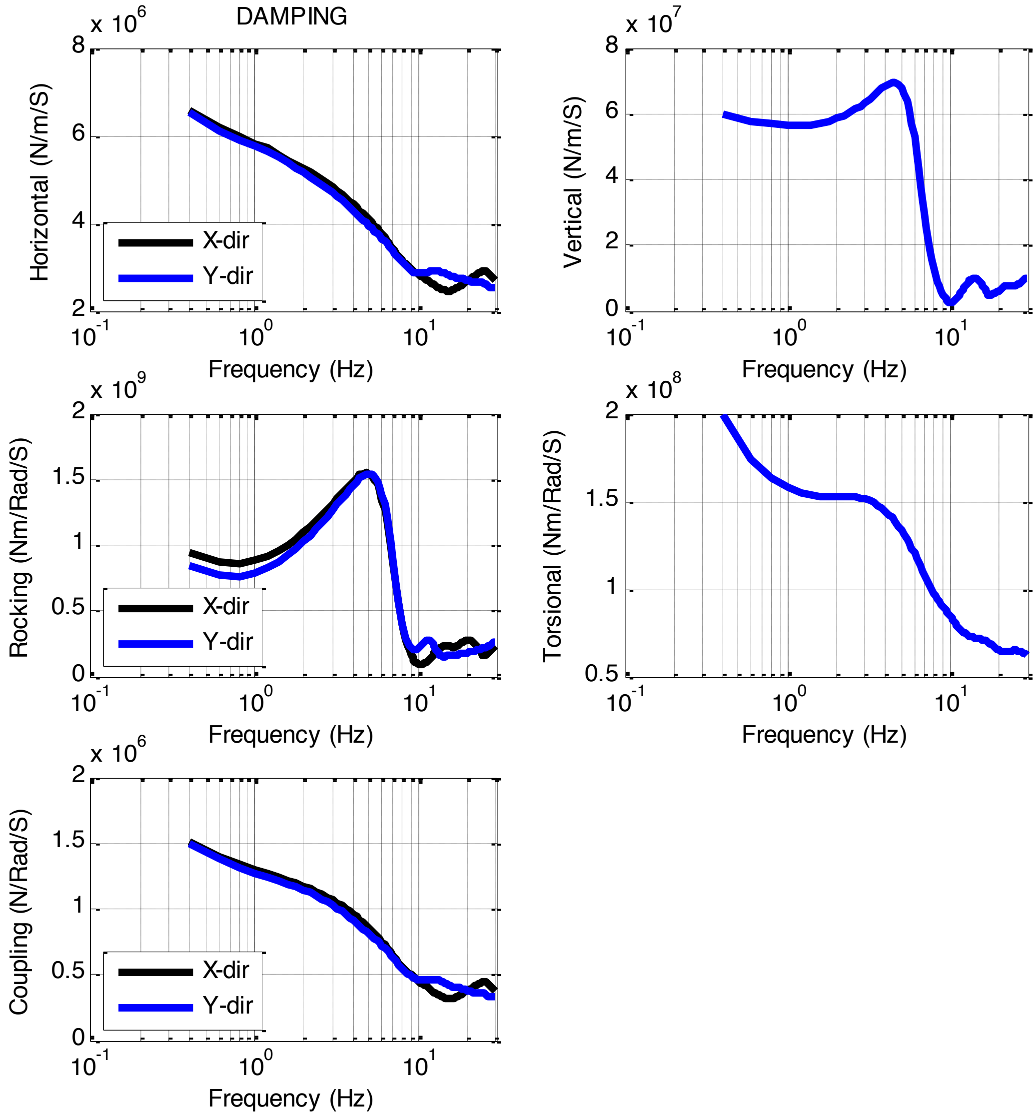


Figure 6.25: Detached Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF3: DAMPING

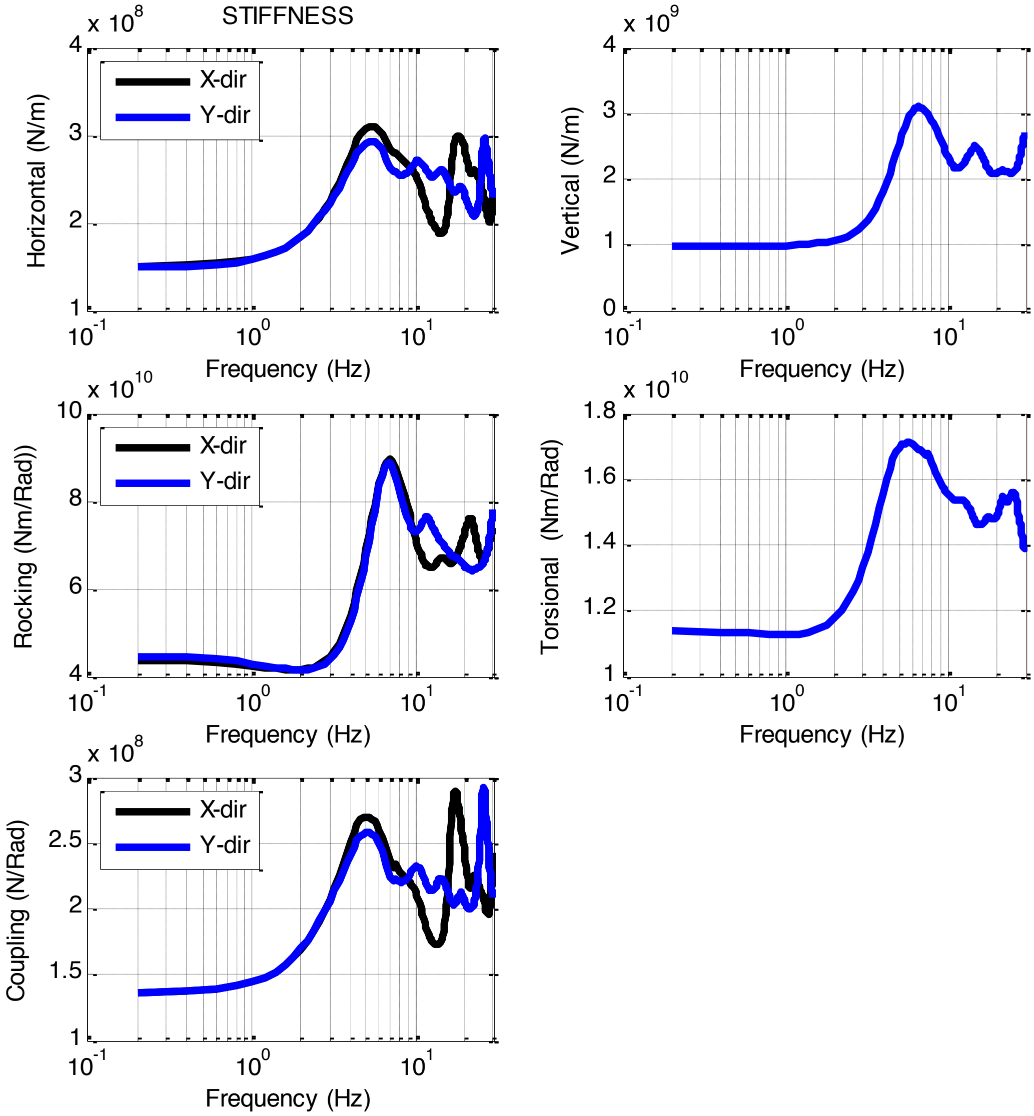


Figure 6.26: Detached Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

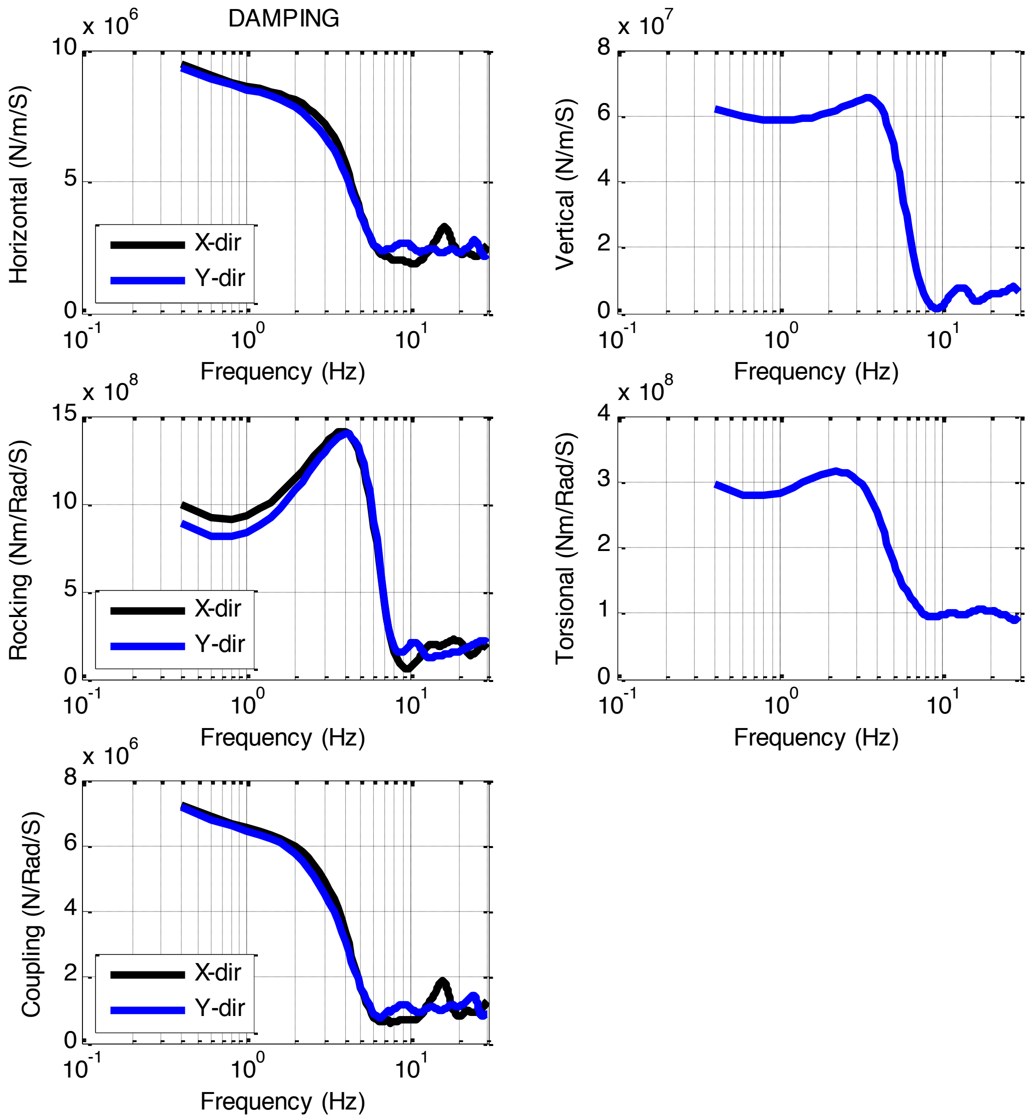


Figure 6.27: Detached Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

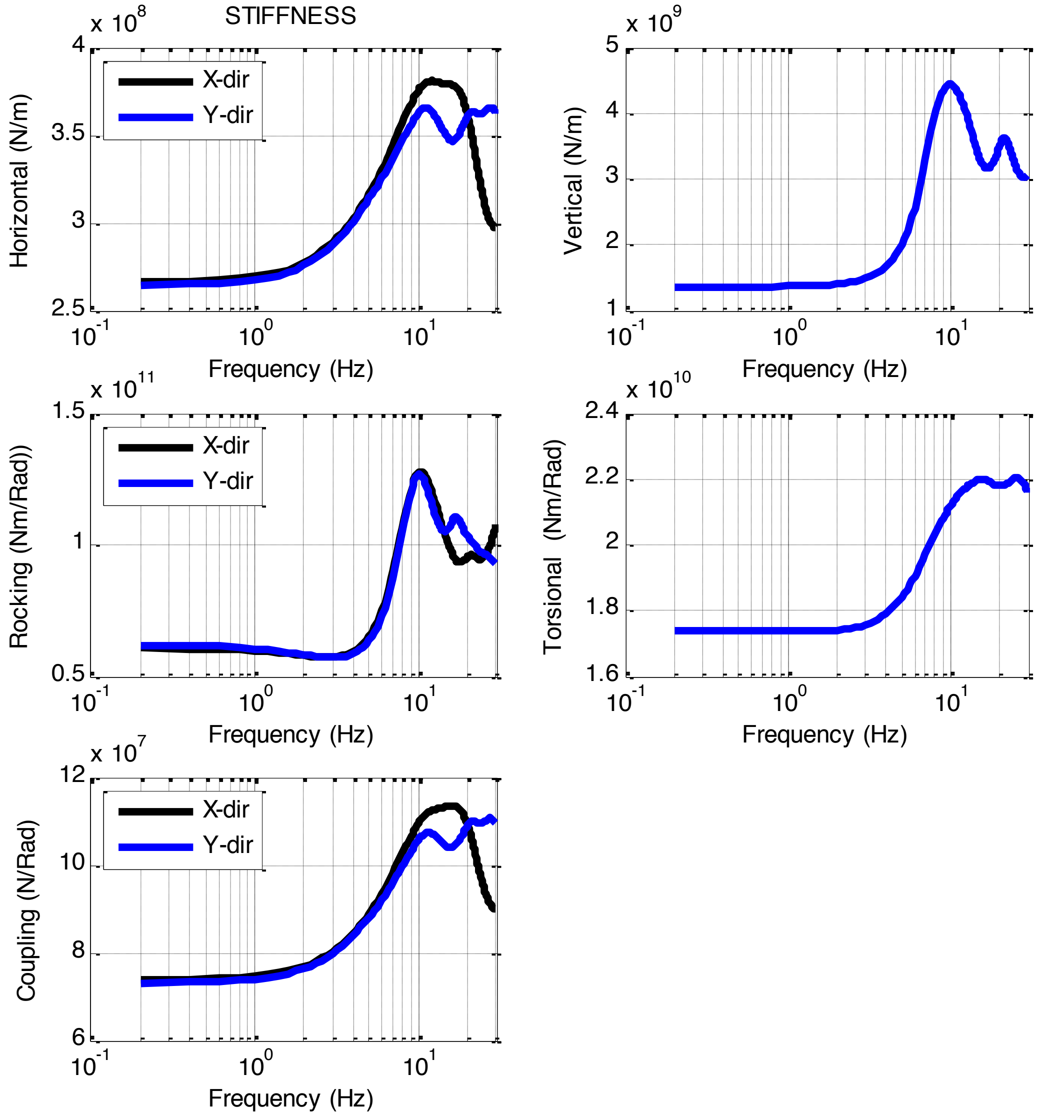


Figure 6.28: Detached Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

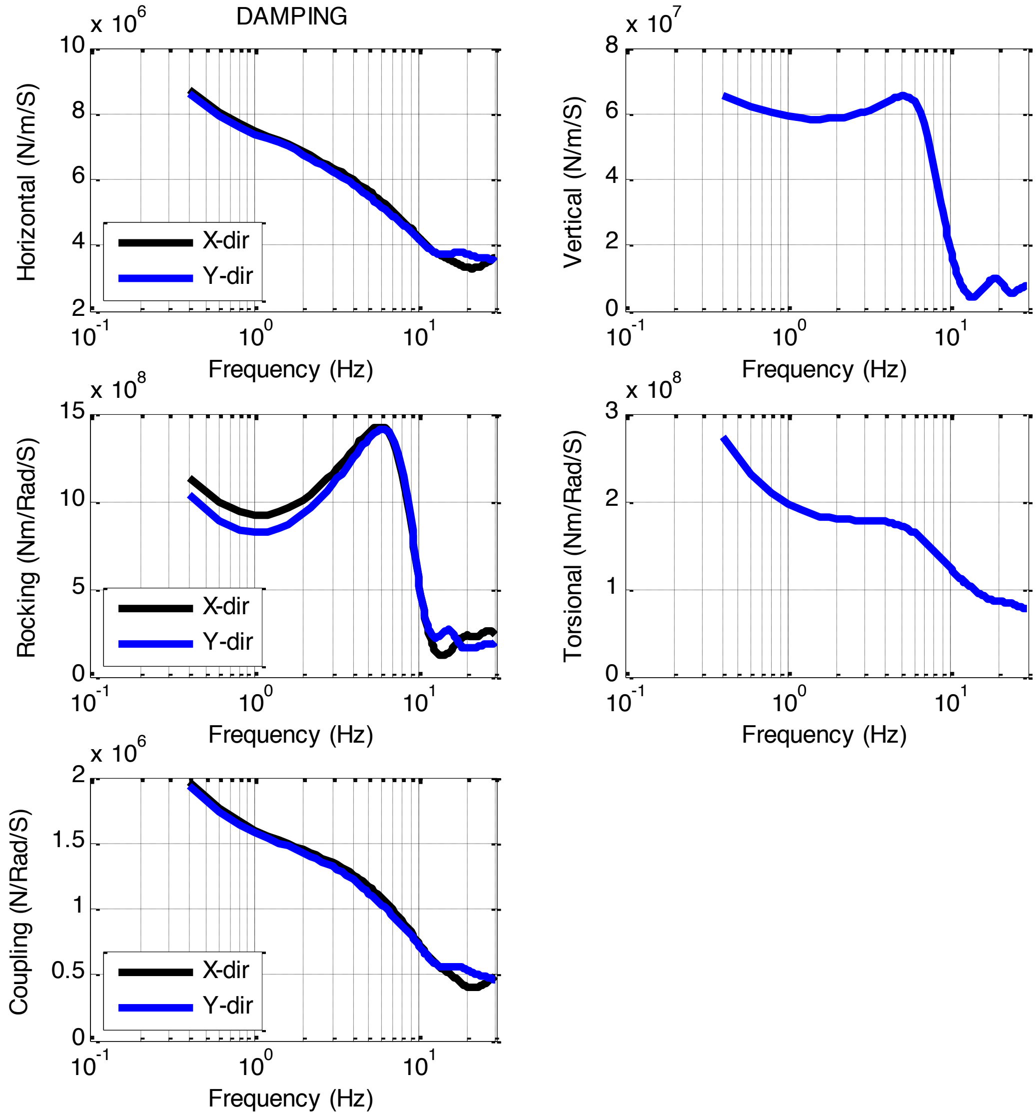


Figure 6.29: Detached Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

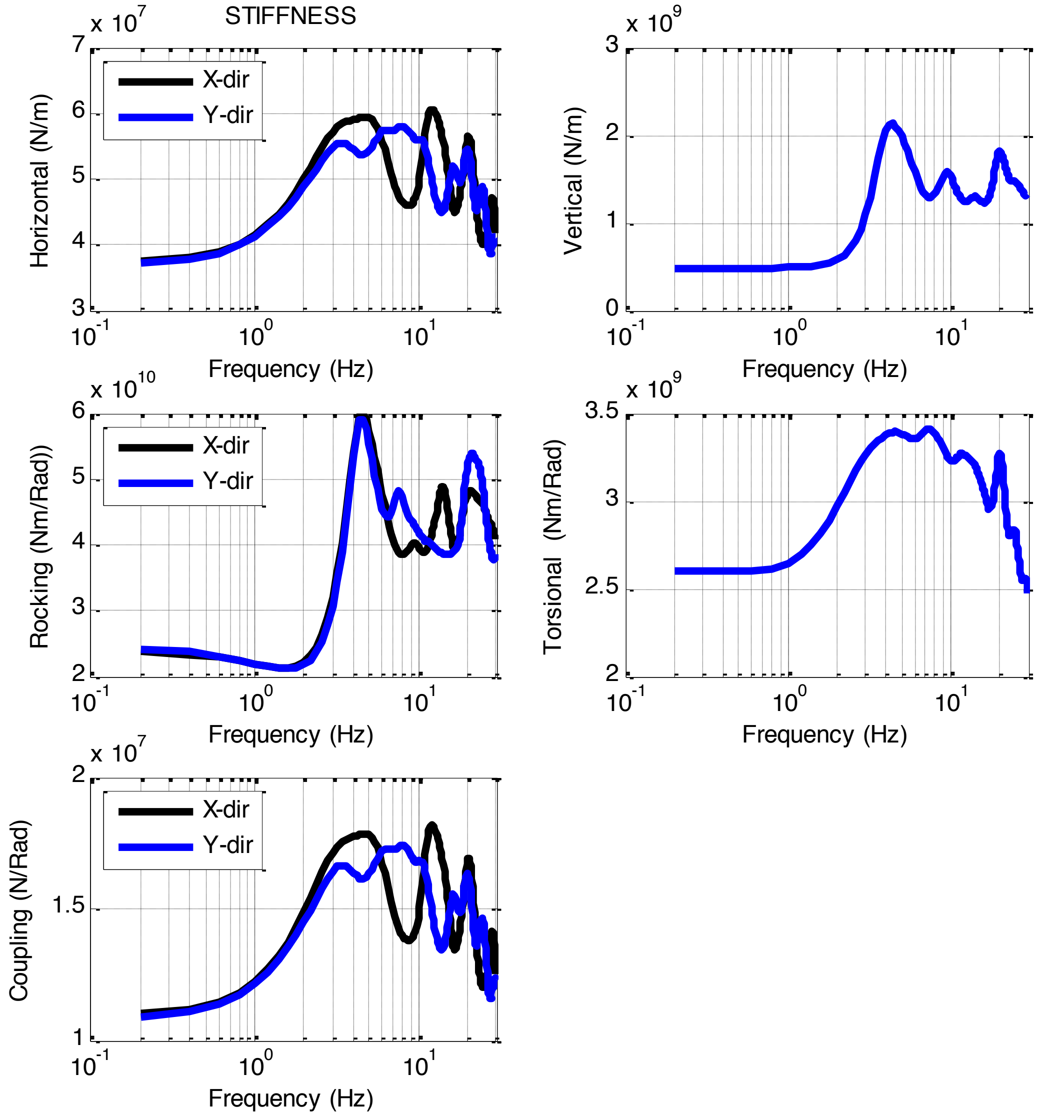


Figure 6.30: Detached Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

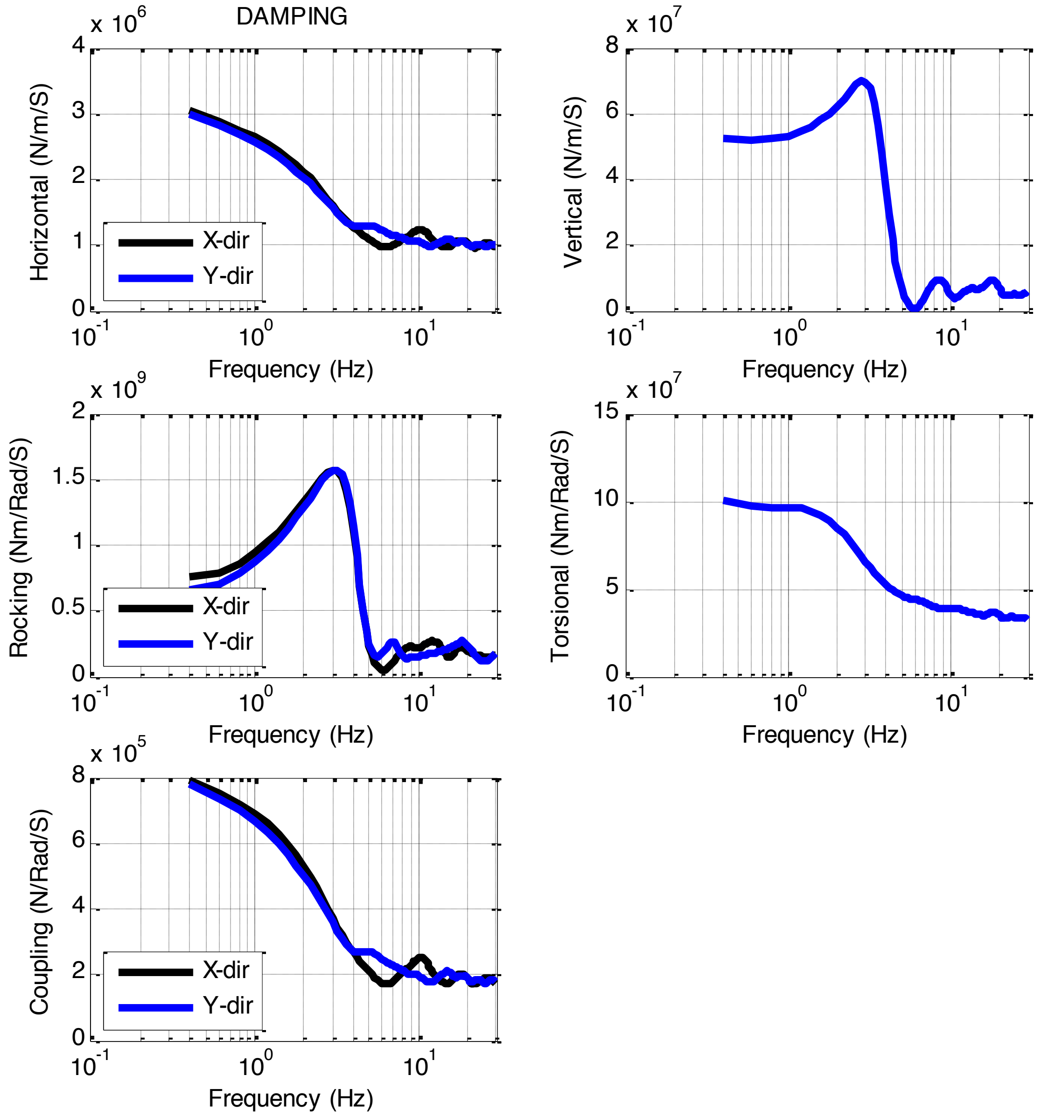


Figure 6.31: Detached Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

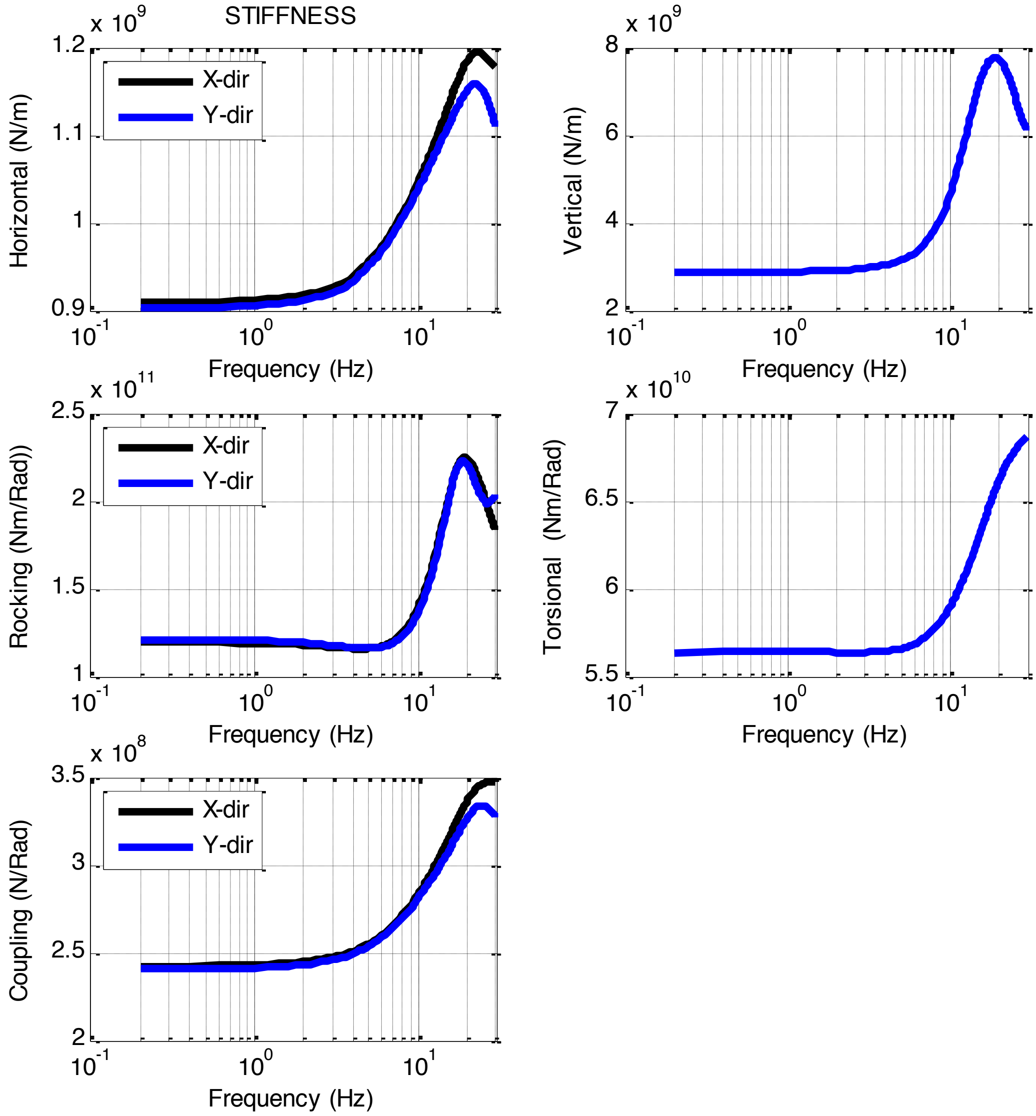


Figure 6.32: Detached Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

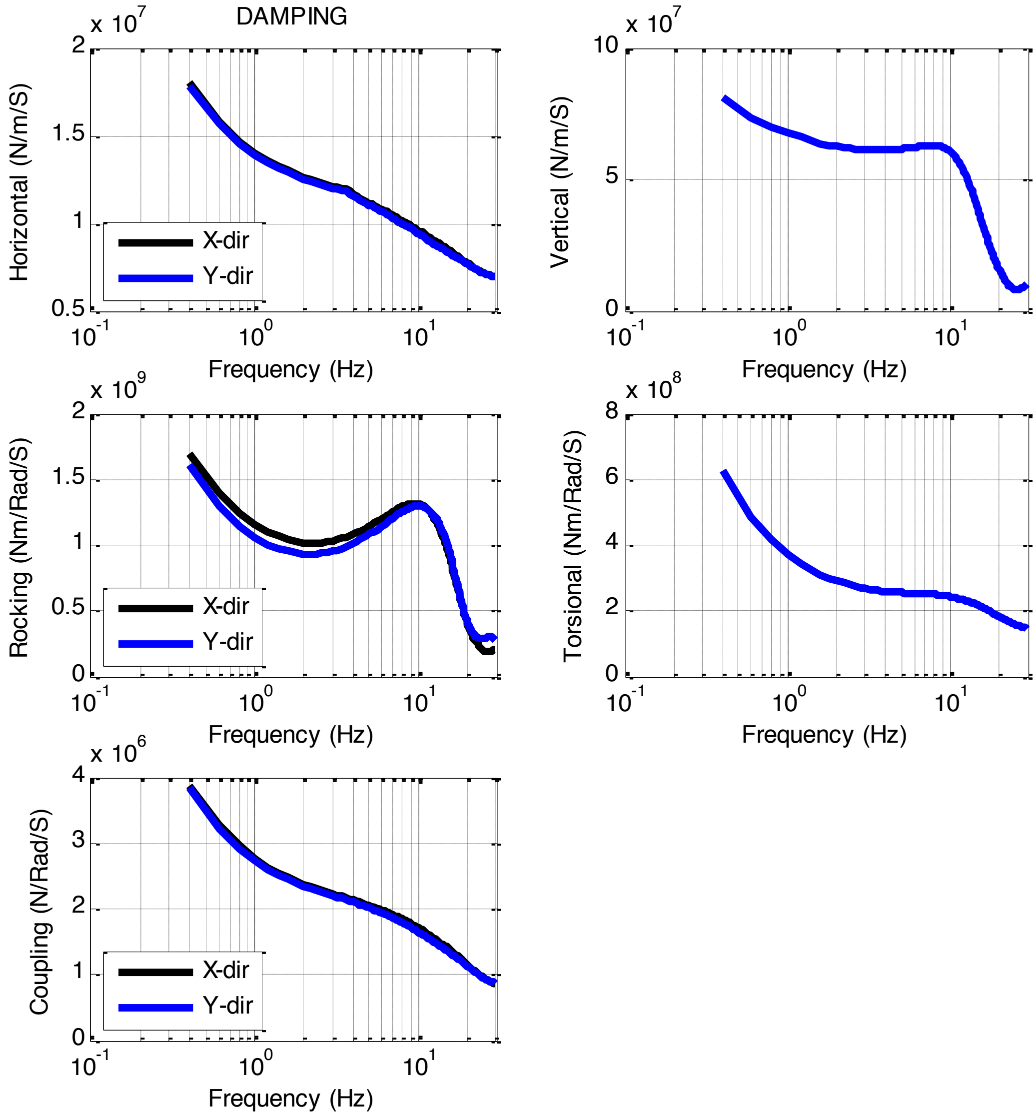


Figure 6.33: Detached Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

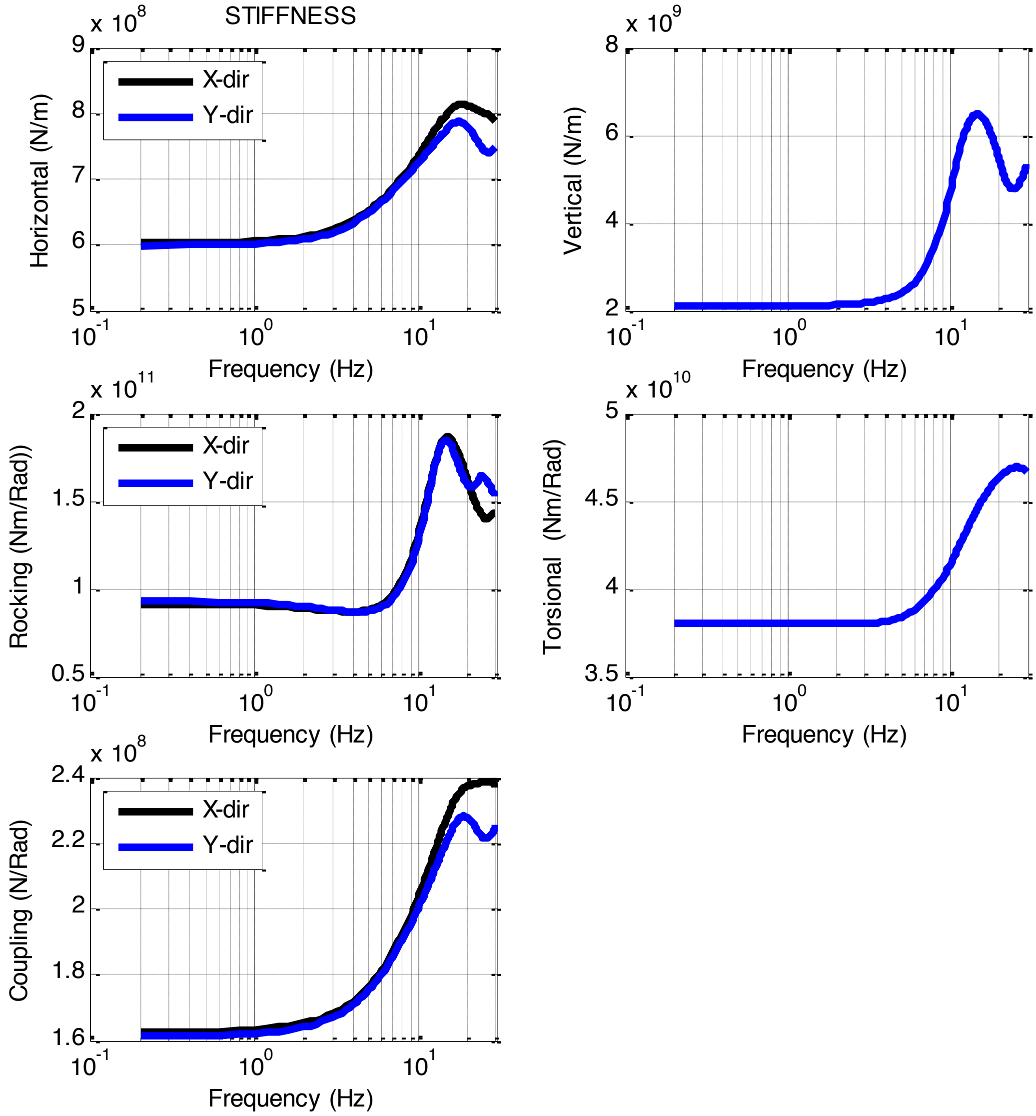


Figure 6.34: Detached Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

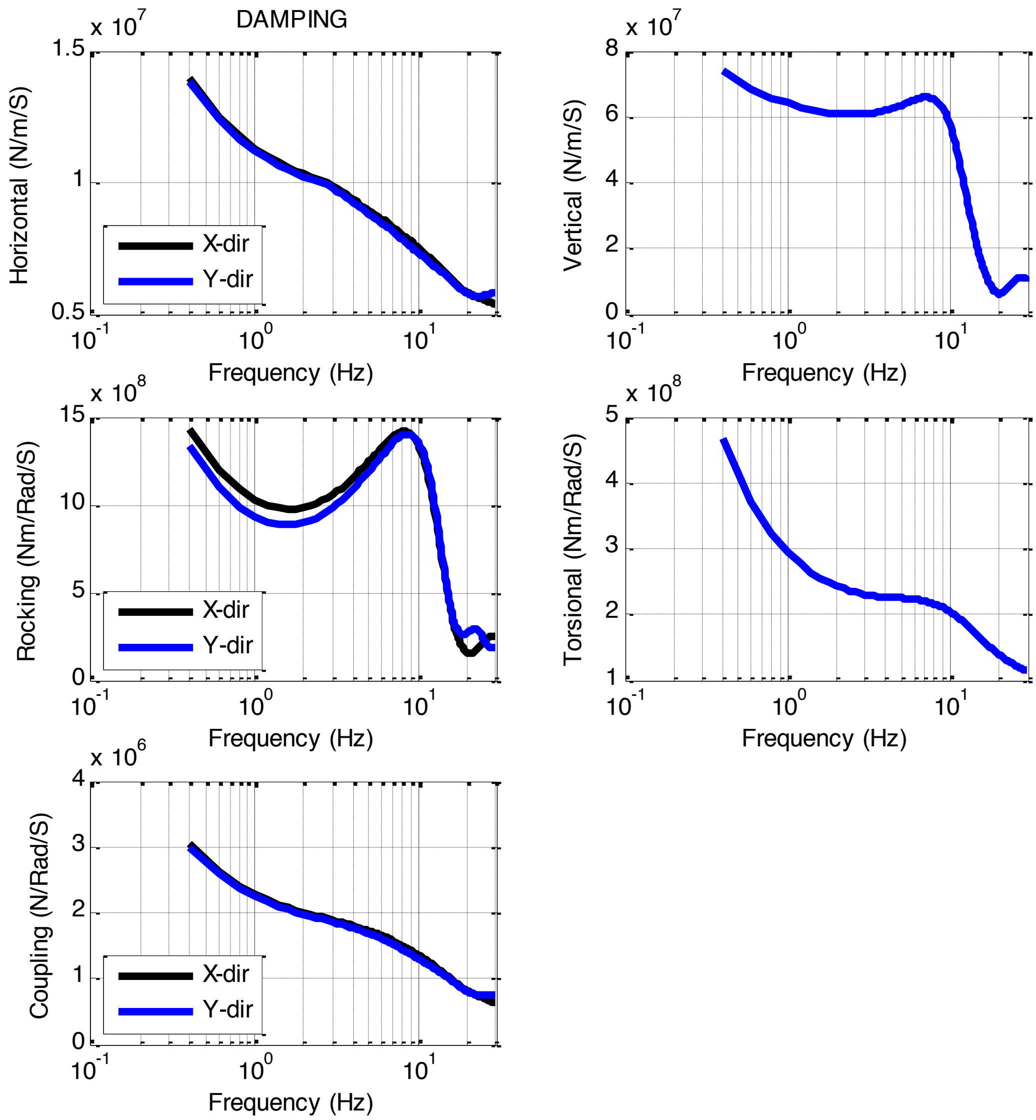


Figure 6.35: Detached Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

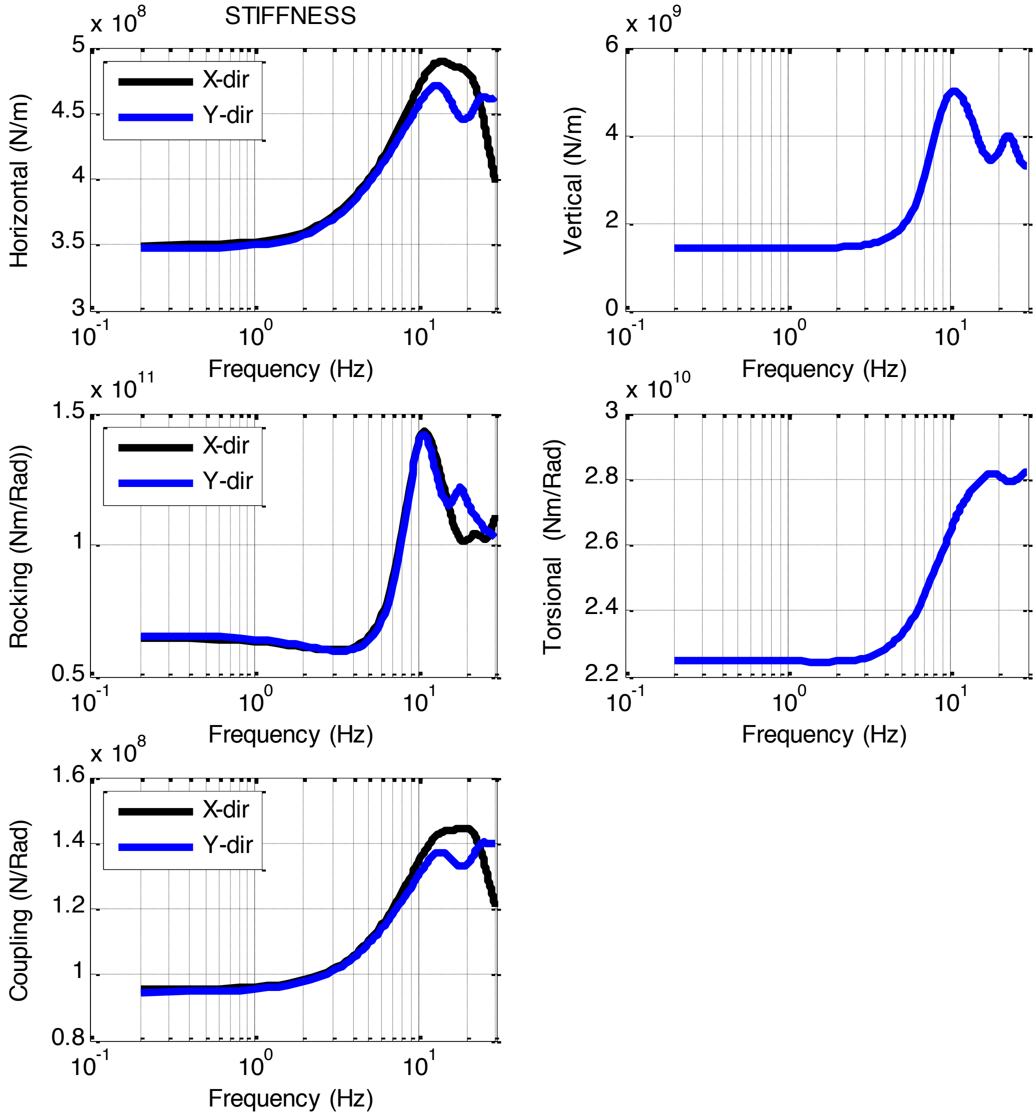


Figure 6.36: Detached Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

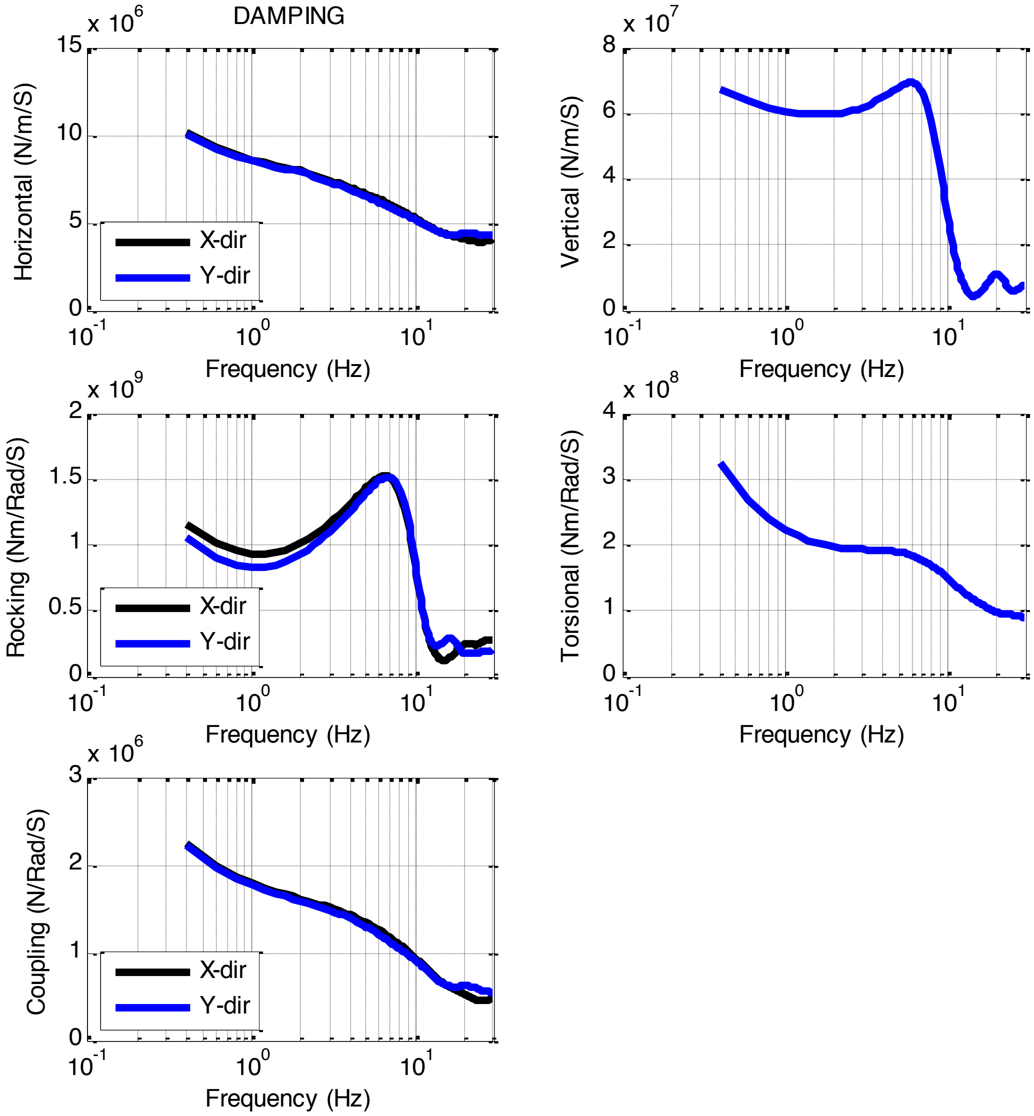


Figure 6.37: Detached Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

6.2 Terraced building, 4 Units

Figure 6.38 shows the scheme of the foundations of the Terraced building typology with 4 units. The following sections, for both fixed and pinned head conditions, shows the impedance functions (in terms of frequency dependent stiffness and damping) of the building taking into account the three reference soil profiles defined in section 4.1.1 and the three scaling factors of section 4.1.2. The characteristics of the cap foundations are summarized in the following table. The foundation consists of 250x250 mm square section concrete piles ($A=0.0625m^2$; $I_{xx}=I_{yy}=0.0003255m^4$; $I_{zz}=0.0006510m^4$). The pile length considered is equal to 16m.

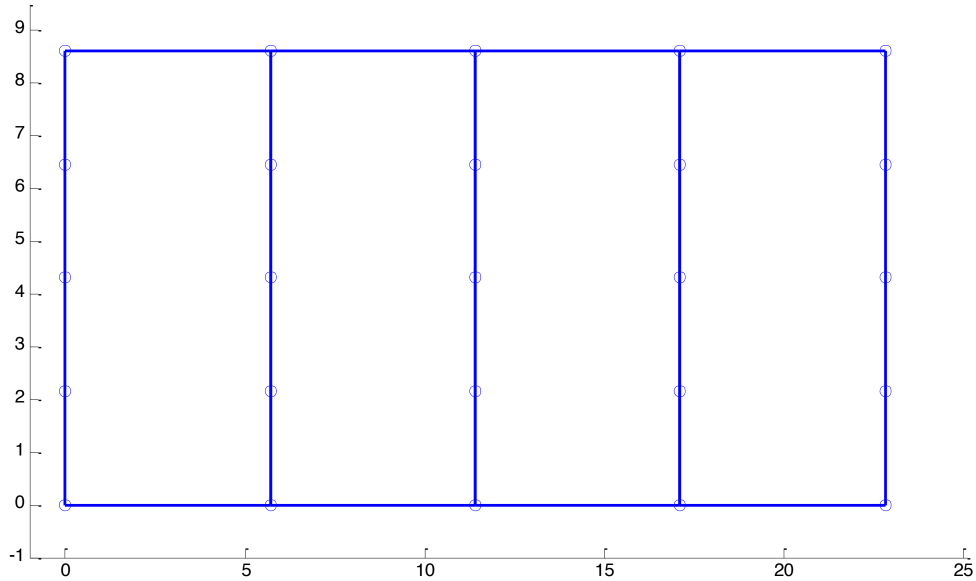


Figure 6.38: Terraced building, 4 units: schematic position of beam foundations and location of piles

Table 6.2: Foundations characteristics of Terrace building, 4 Units

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m²]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m²]	I_{yy} [kg m²]	I_{zz} [kg m²]	I_{xy} [kg m²]	I_{xz} [kg m²]	I_{yz} [kg m²]
22.8	8.4	0.6	45.8	11.01	4.16	68.6e3	762.7e3	3199.6e3	3958.2e3	0	0	0

6.2.1 Fixed head conditions

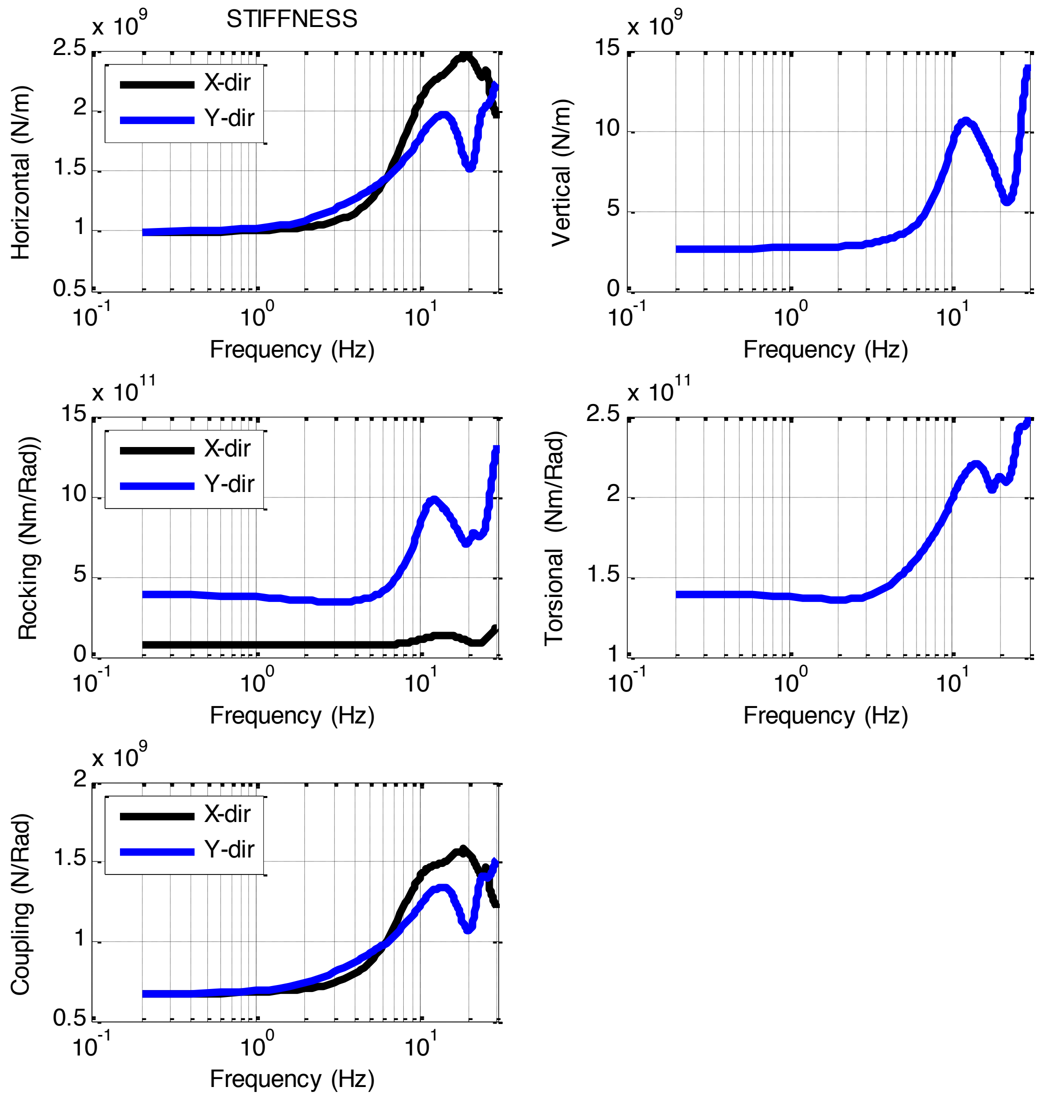


Figure 6.39: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF1: STIFFNESS

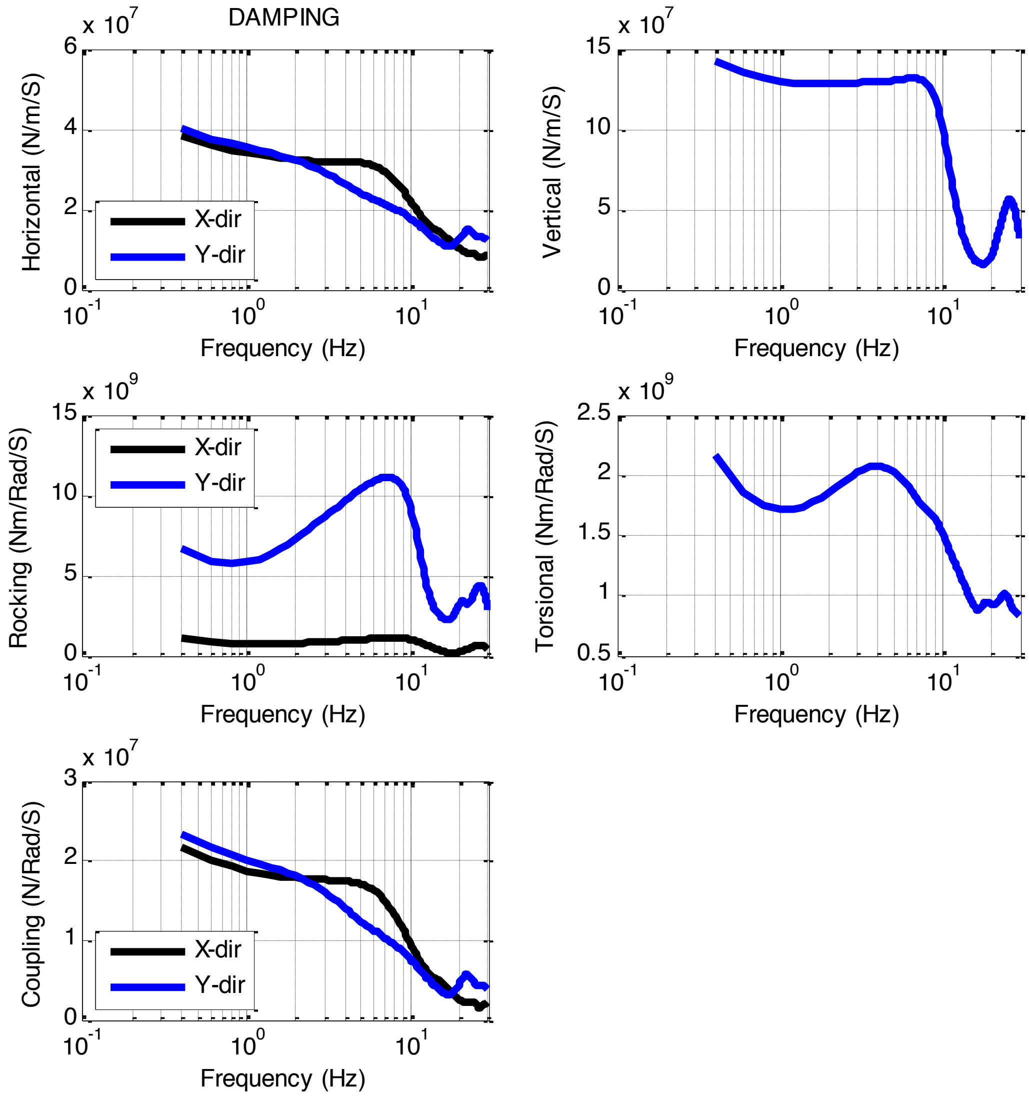


Figure 6.40: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF1: DAMPING

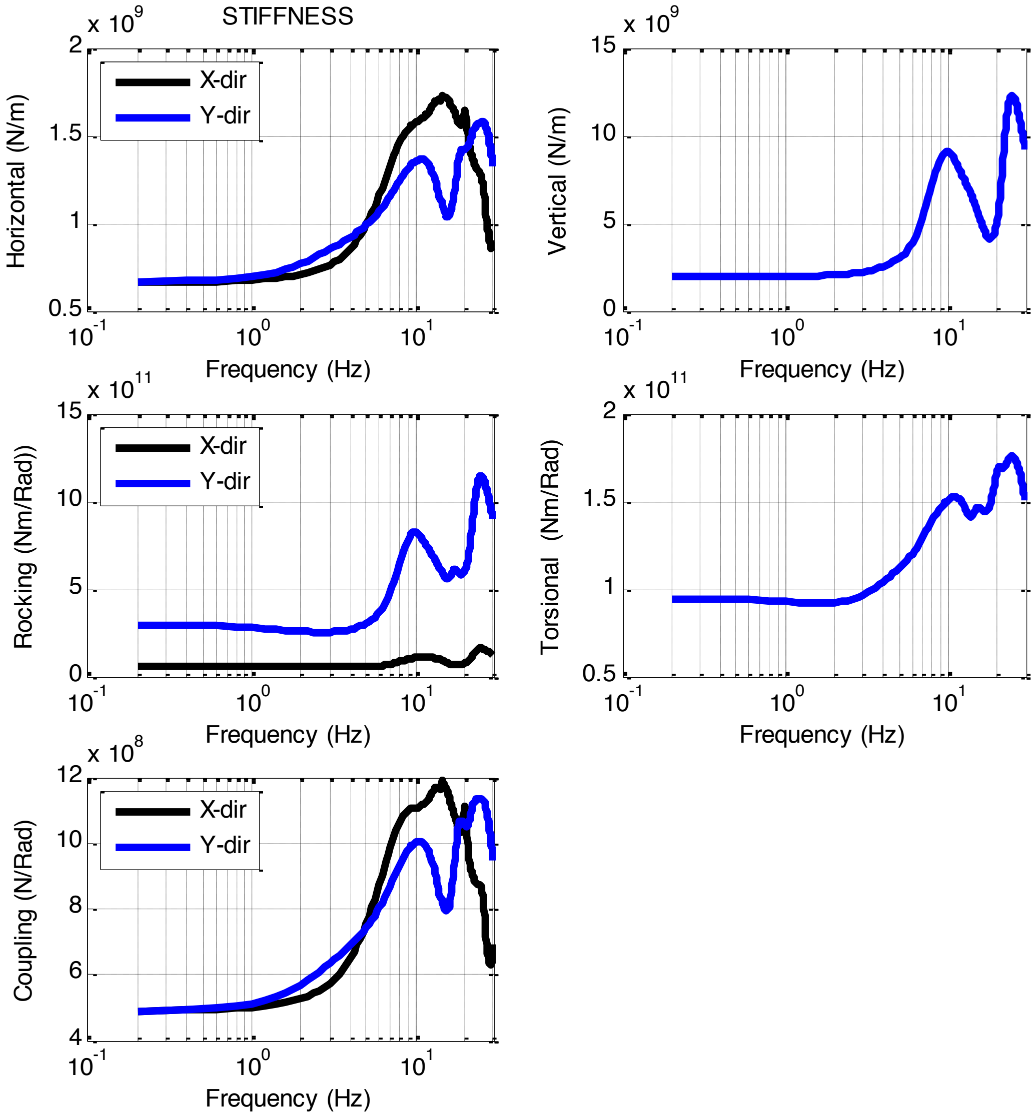


Figure 6.41: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF2: STIFFNESS

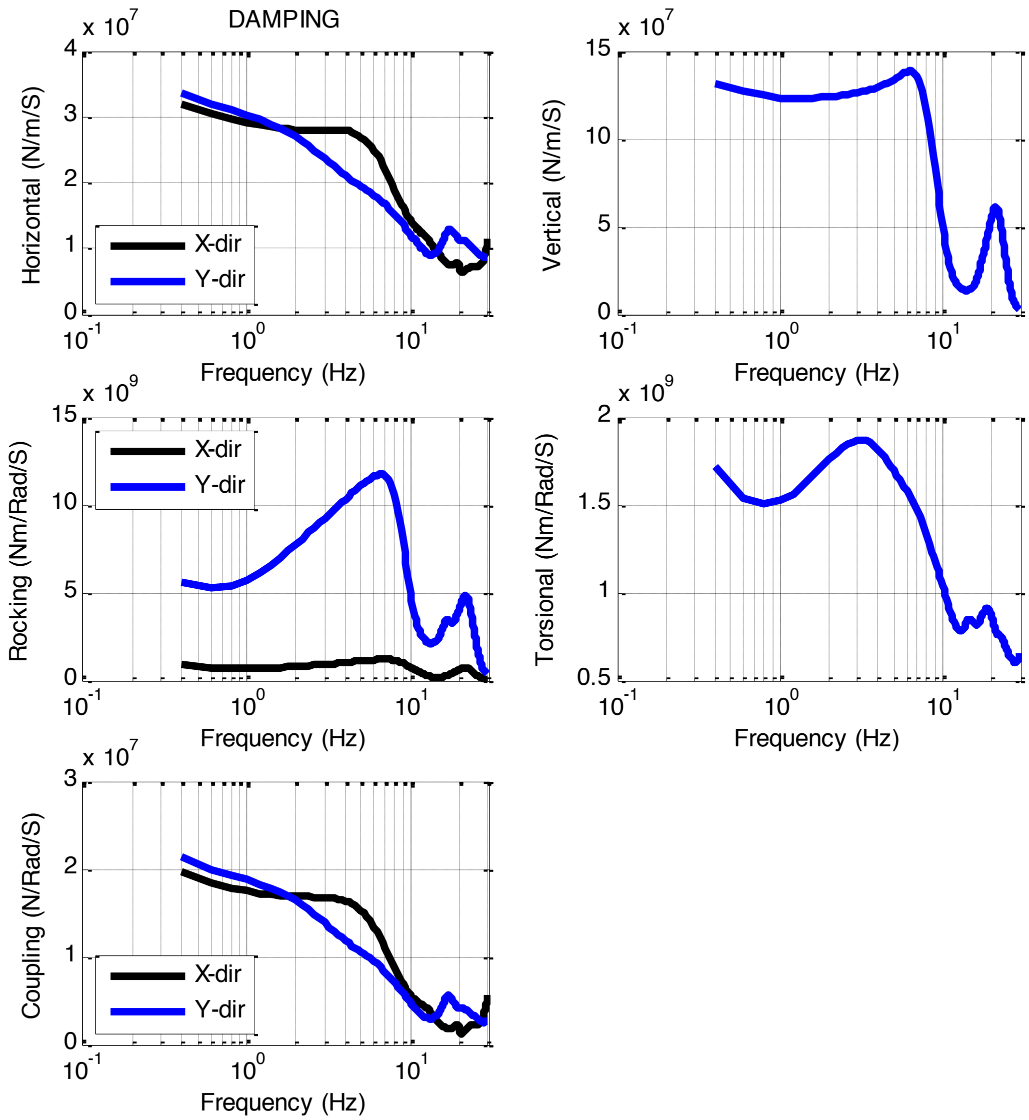


Figure 6.42: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF2: DAMPING

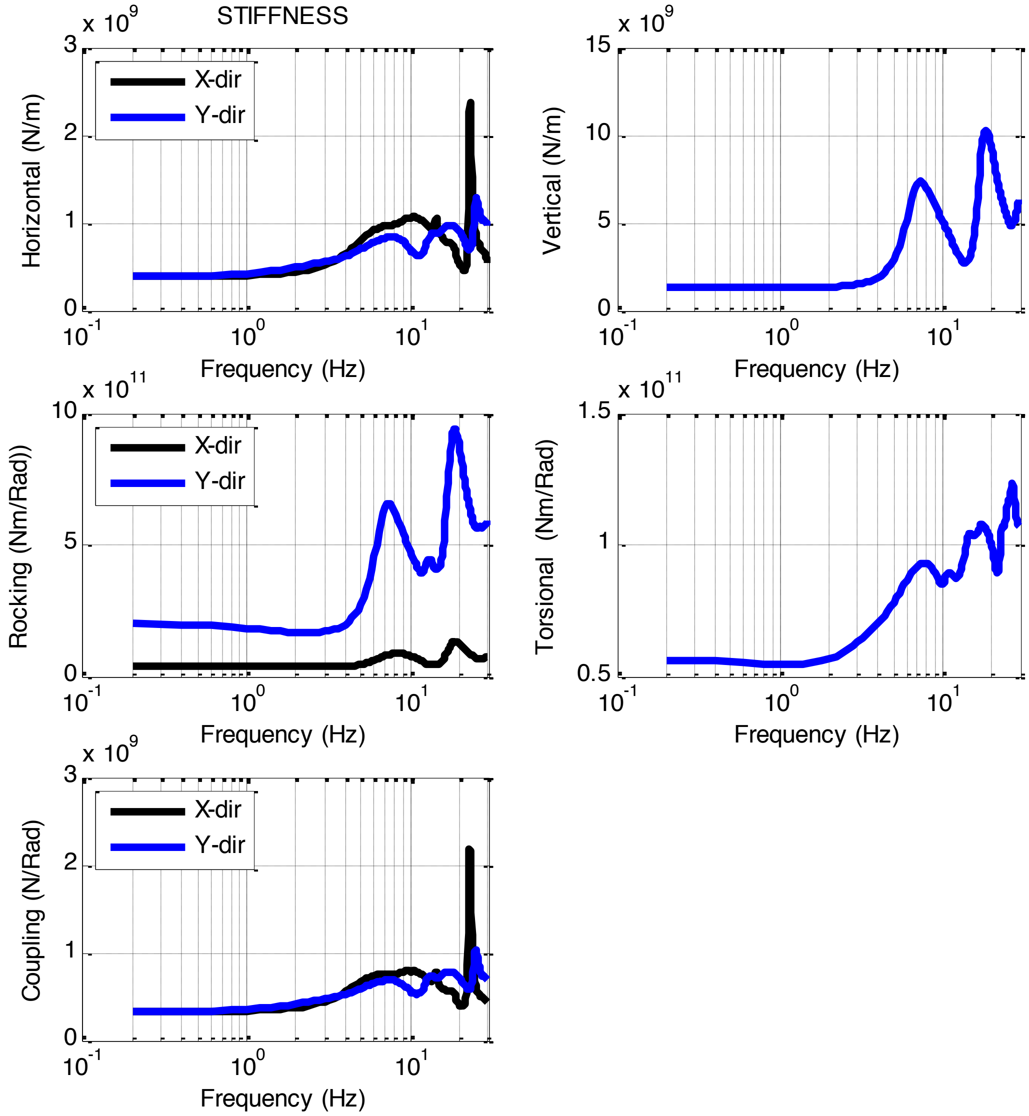


Figure 6.43: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF3: STIFFNESS

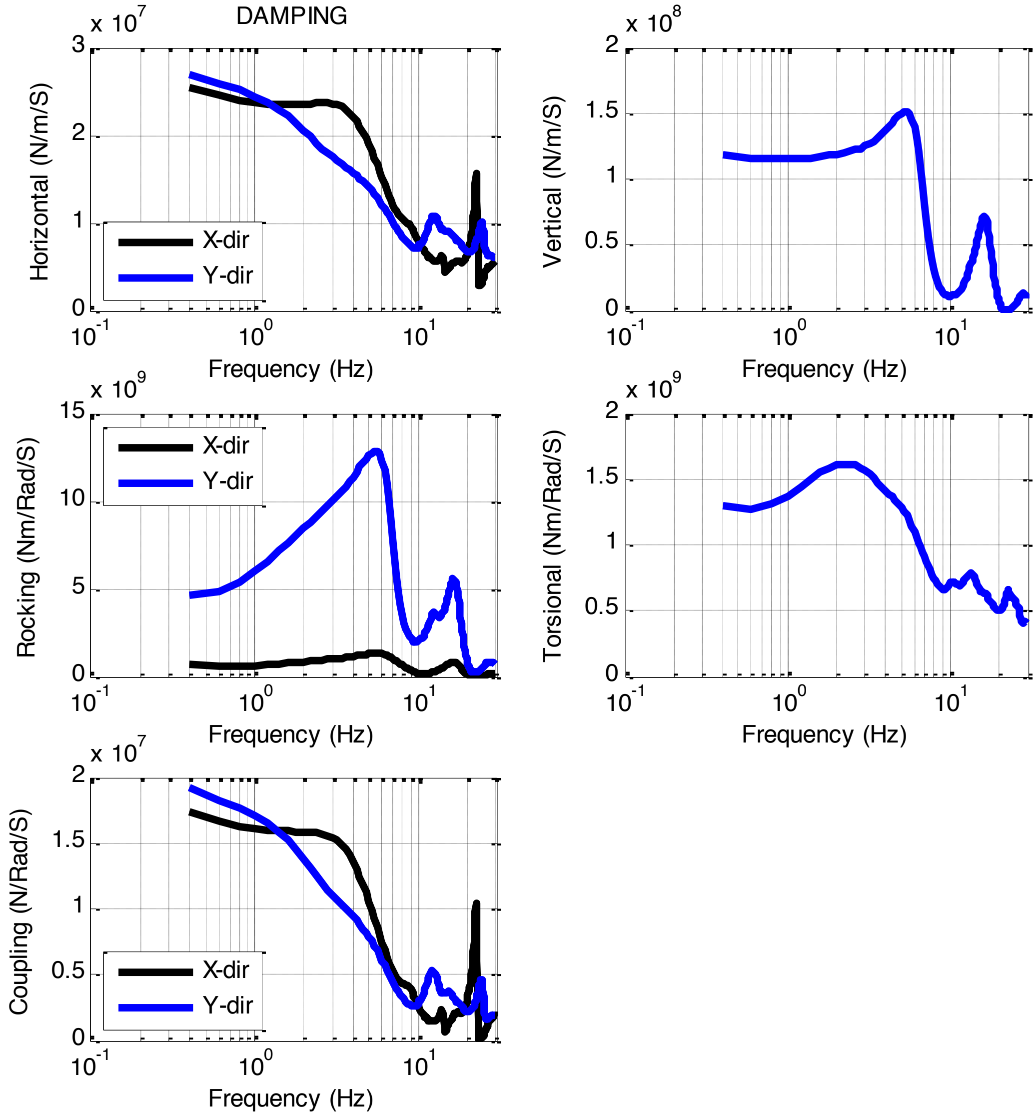


Figure 6.44: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF3: DAMPING

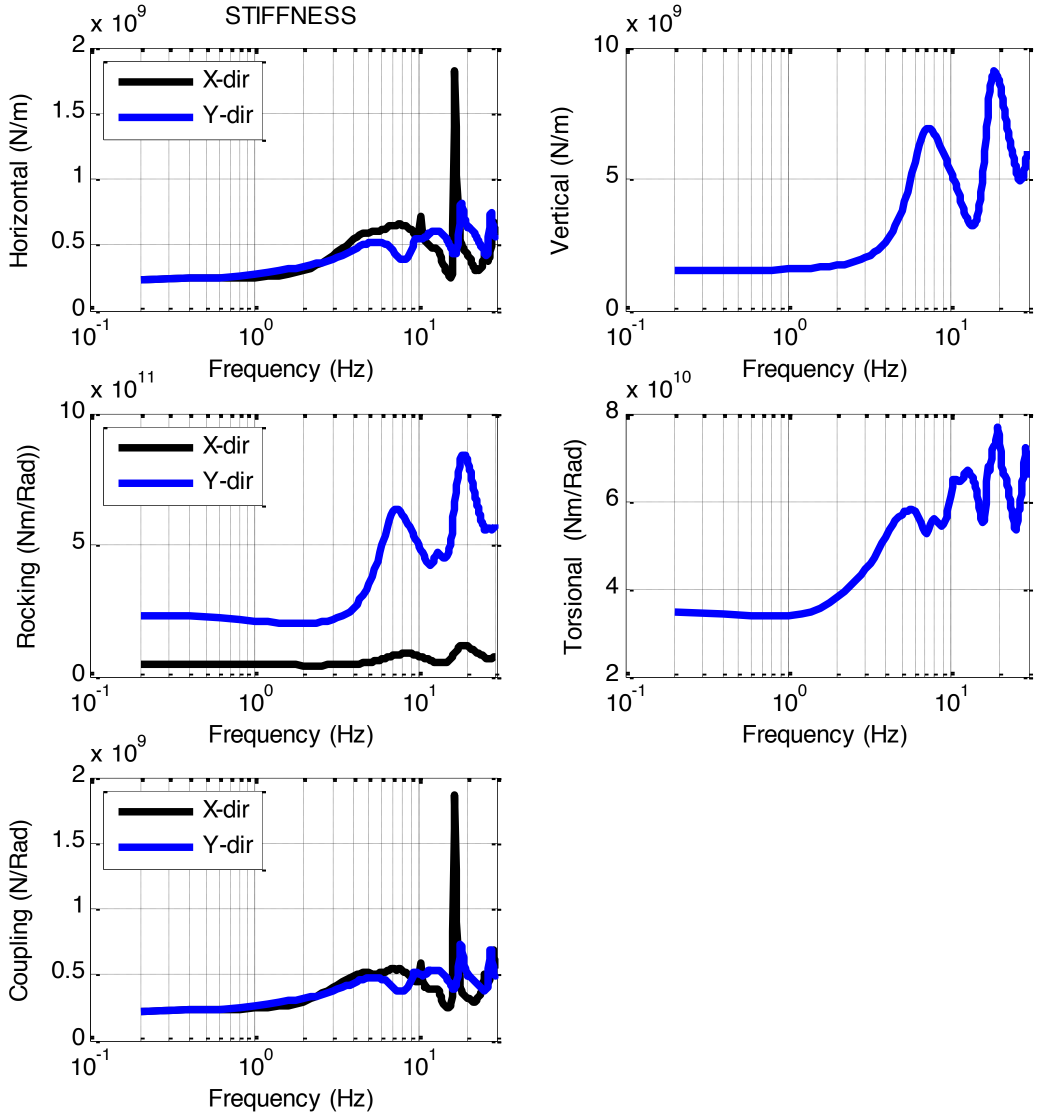


Figure 6.45: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

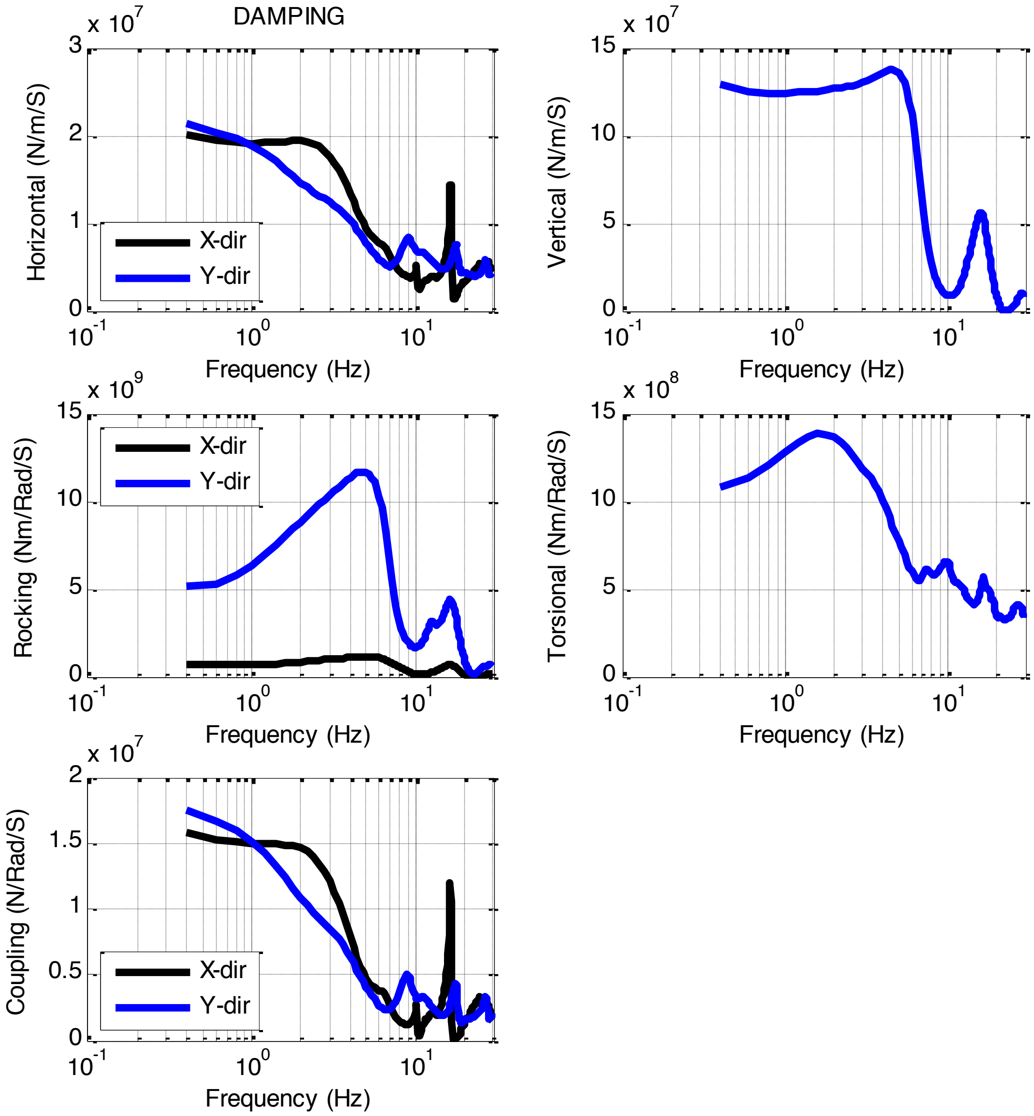


Figure 6.46: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

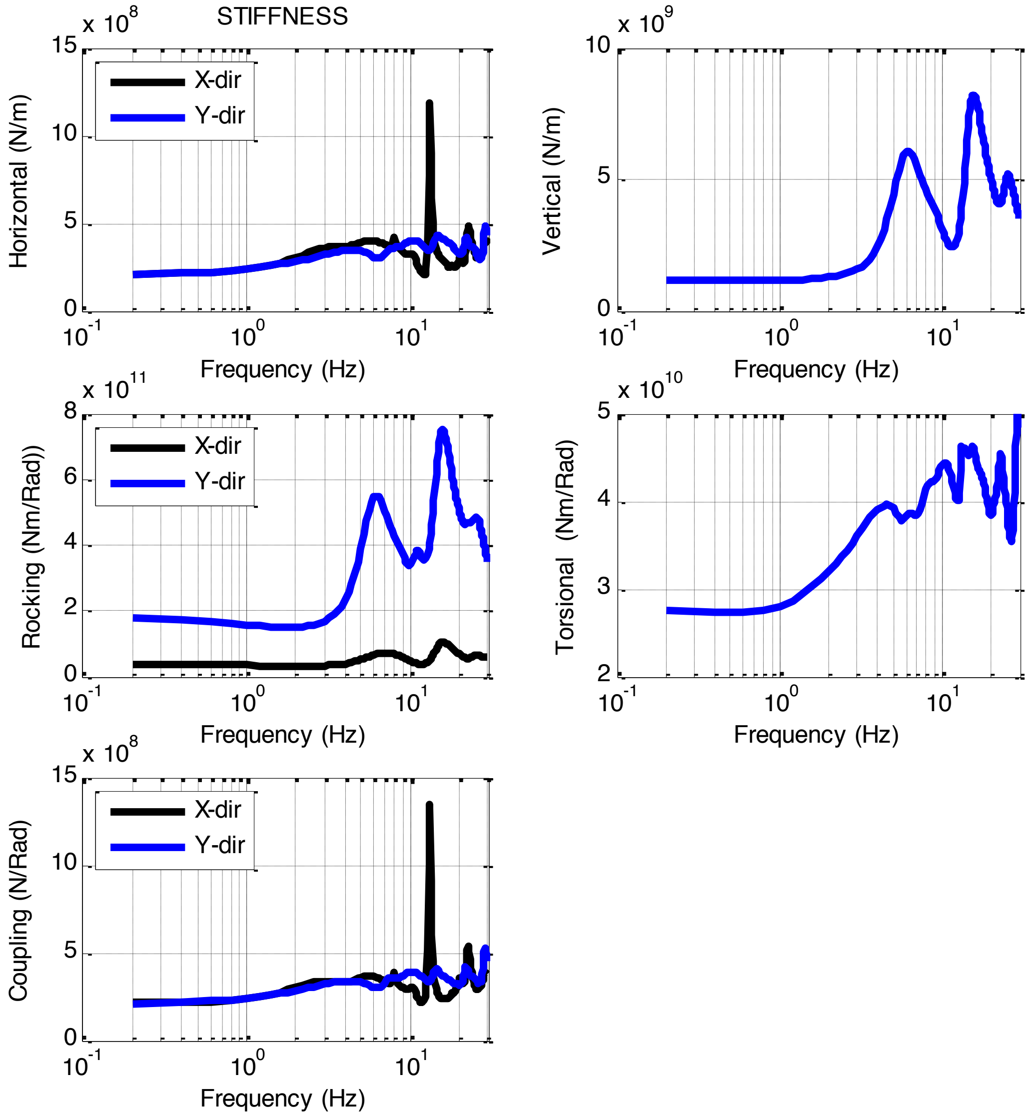


Figure 6.47: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

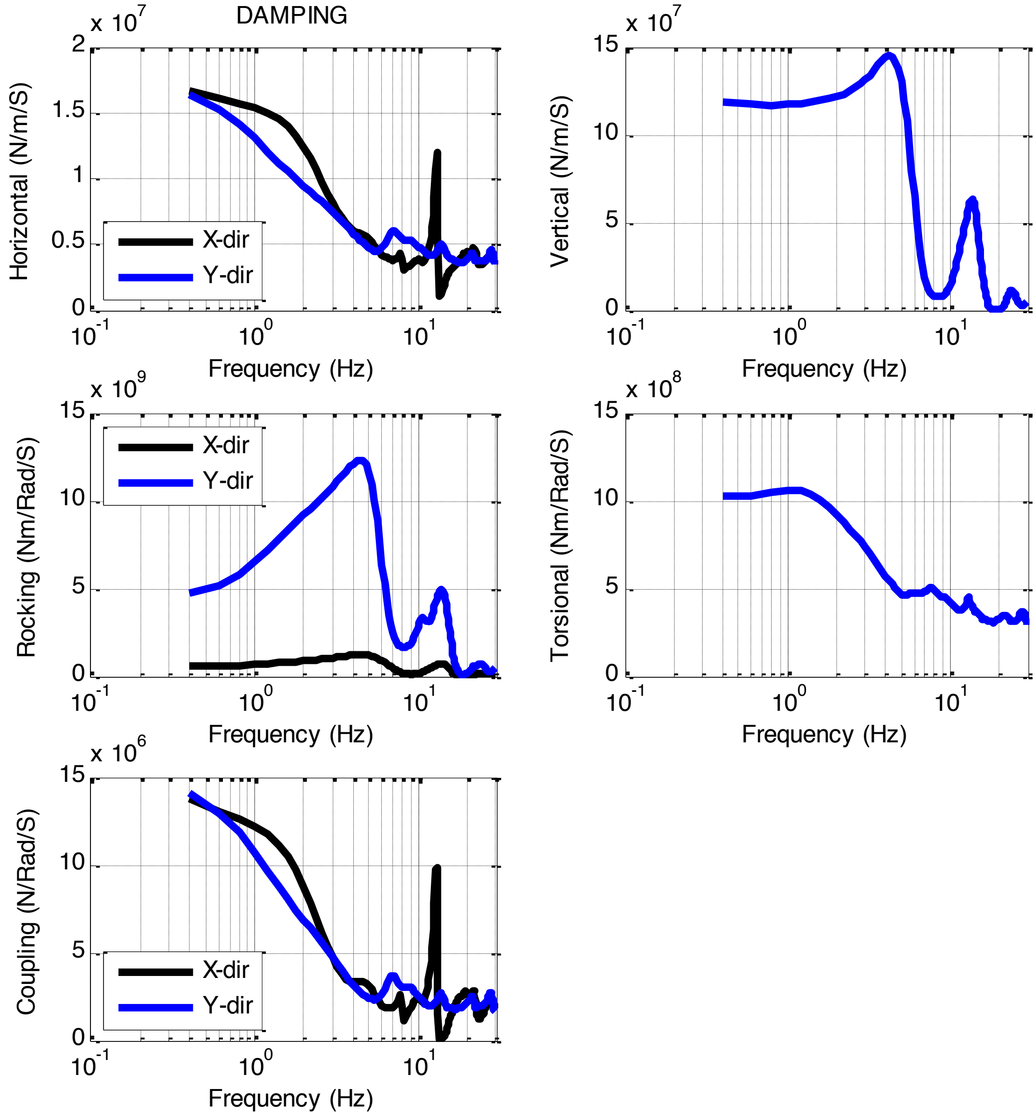


Figure 6.48: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

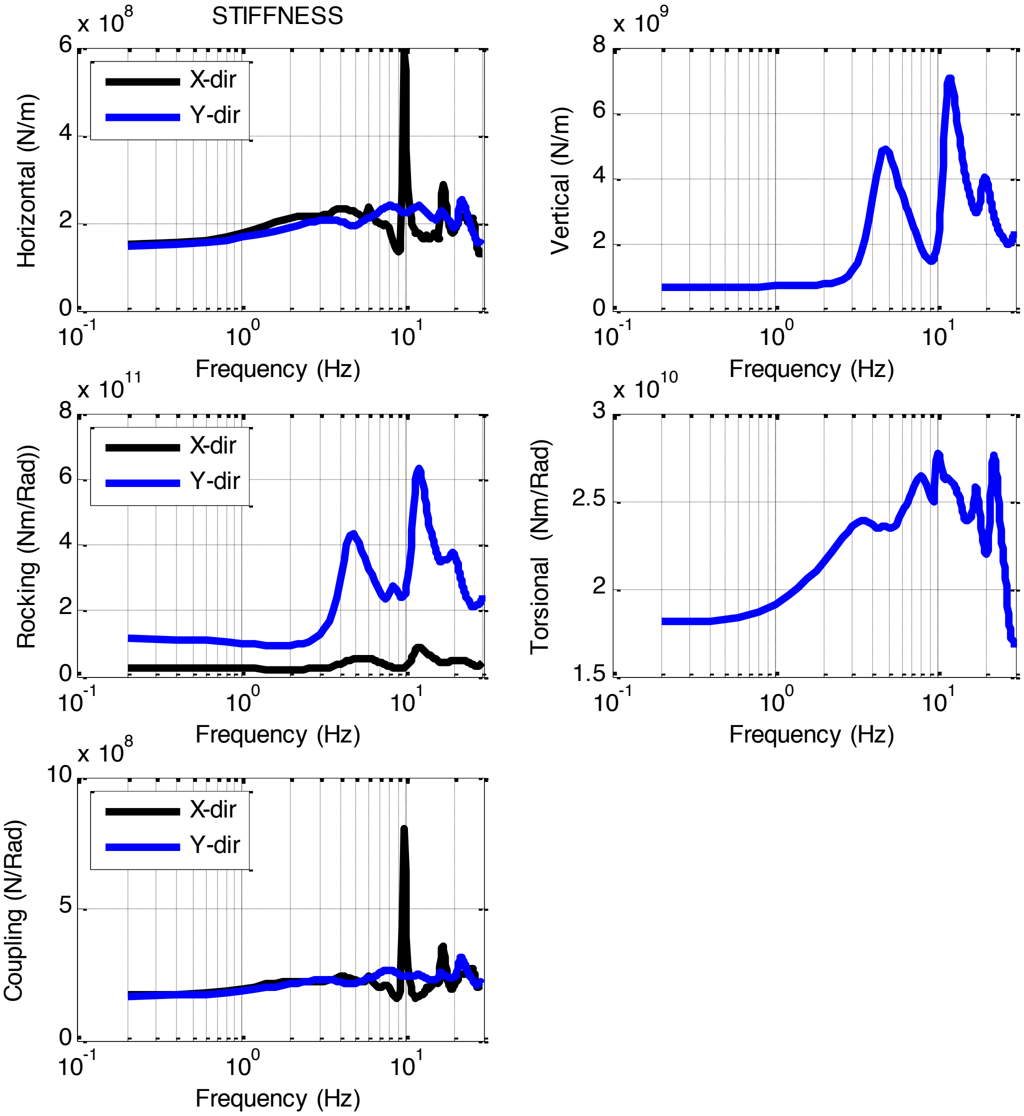


Figure 6.49: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

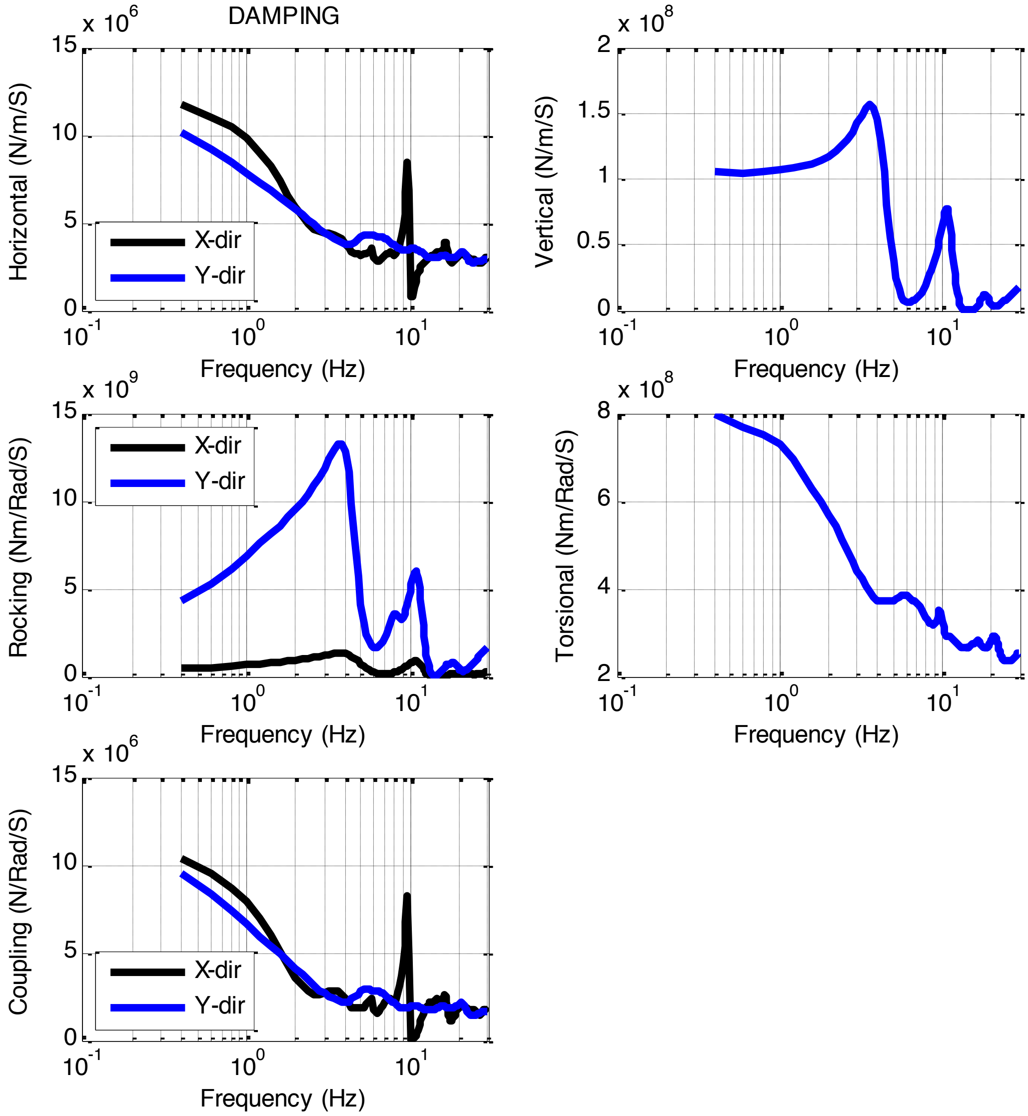


Figure 6.50: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

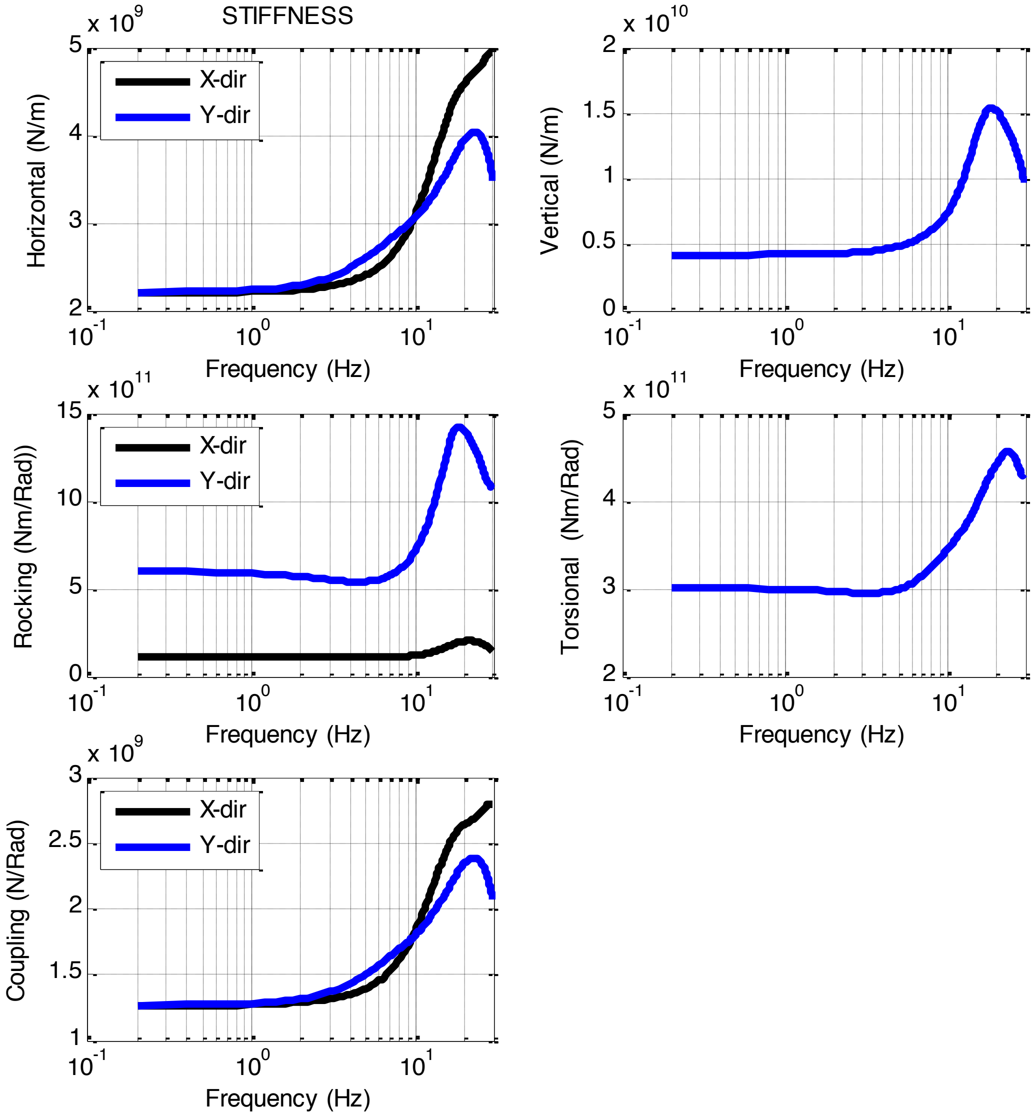


Figure 6.51: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

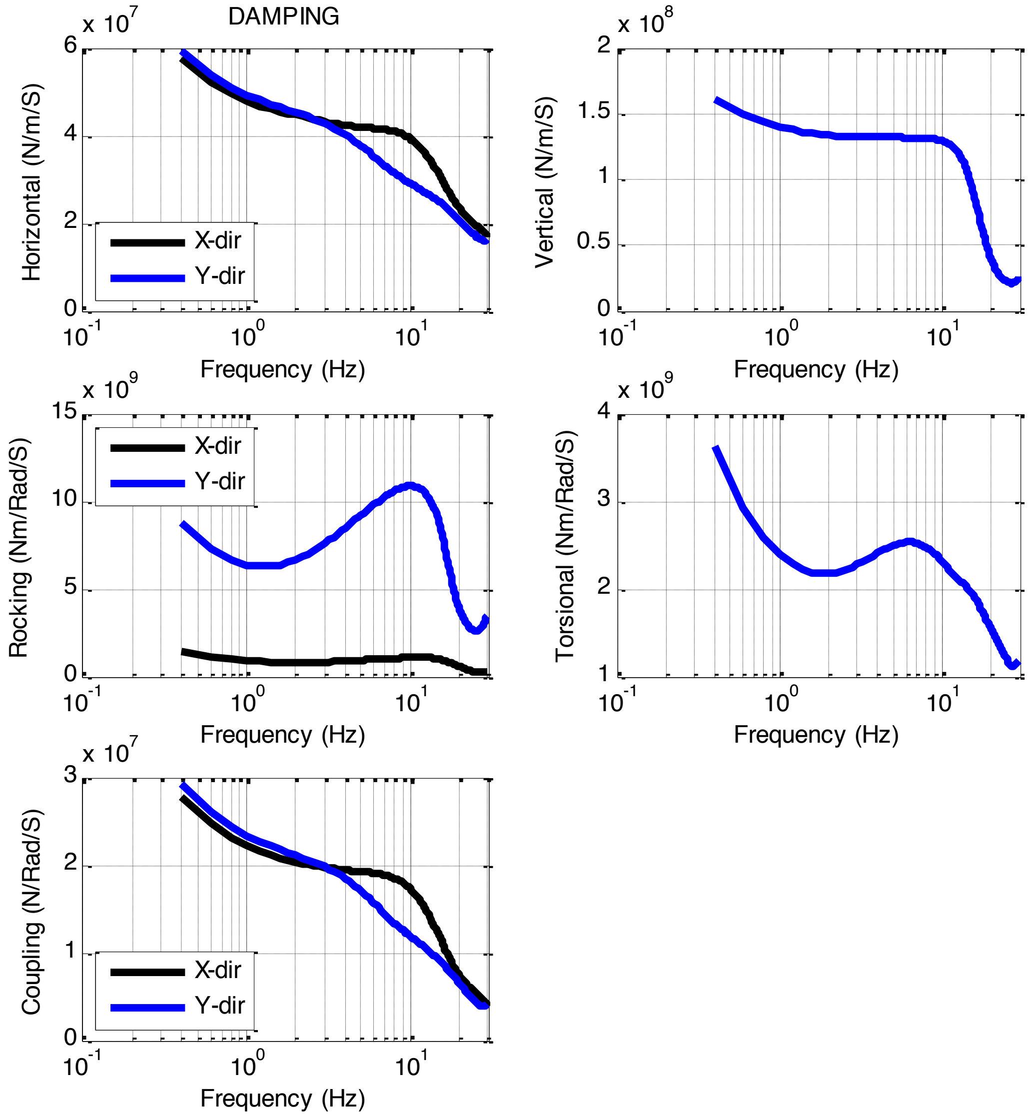


Figure 6.52: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

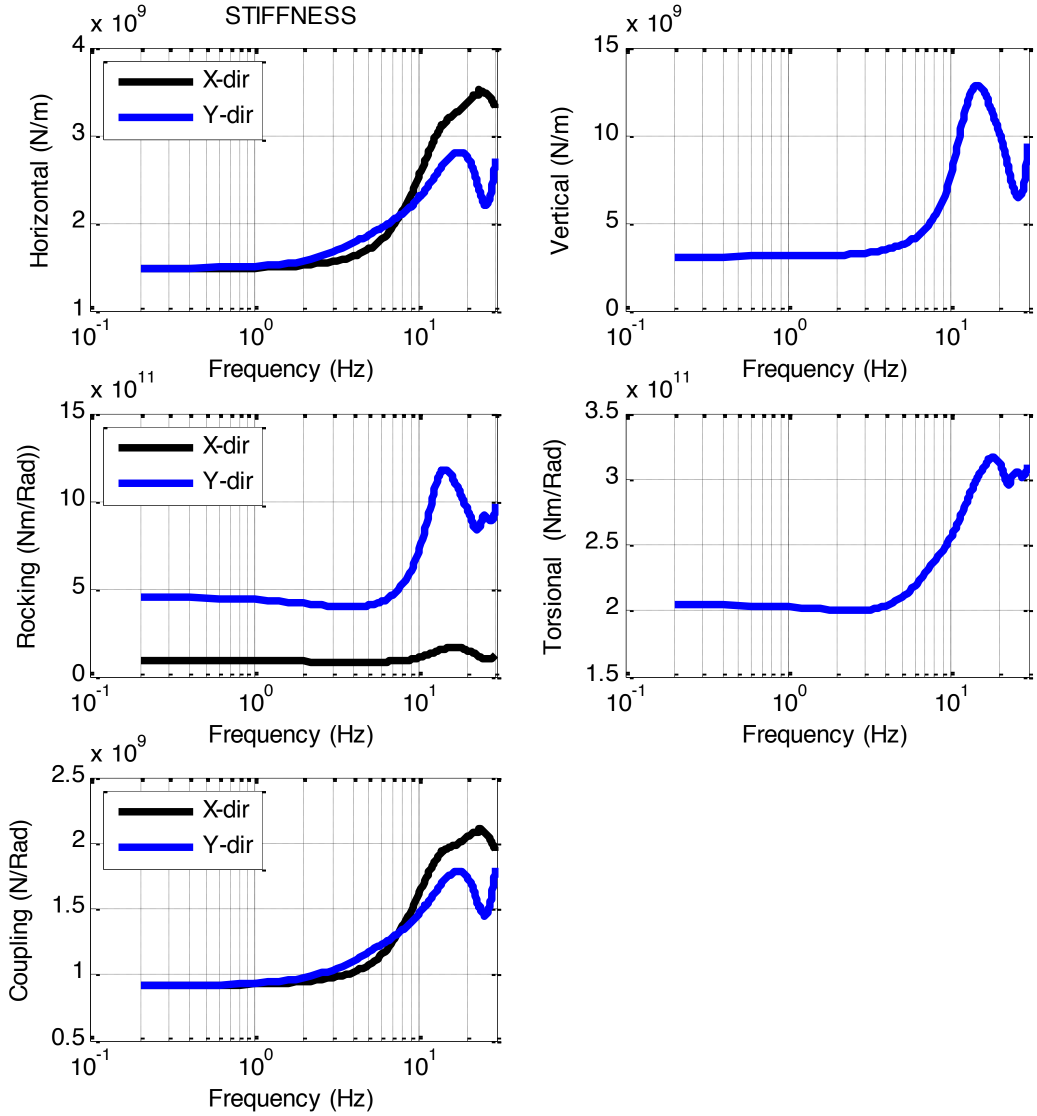


Figure 6.53: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

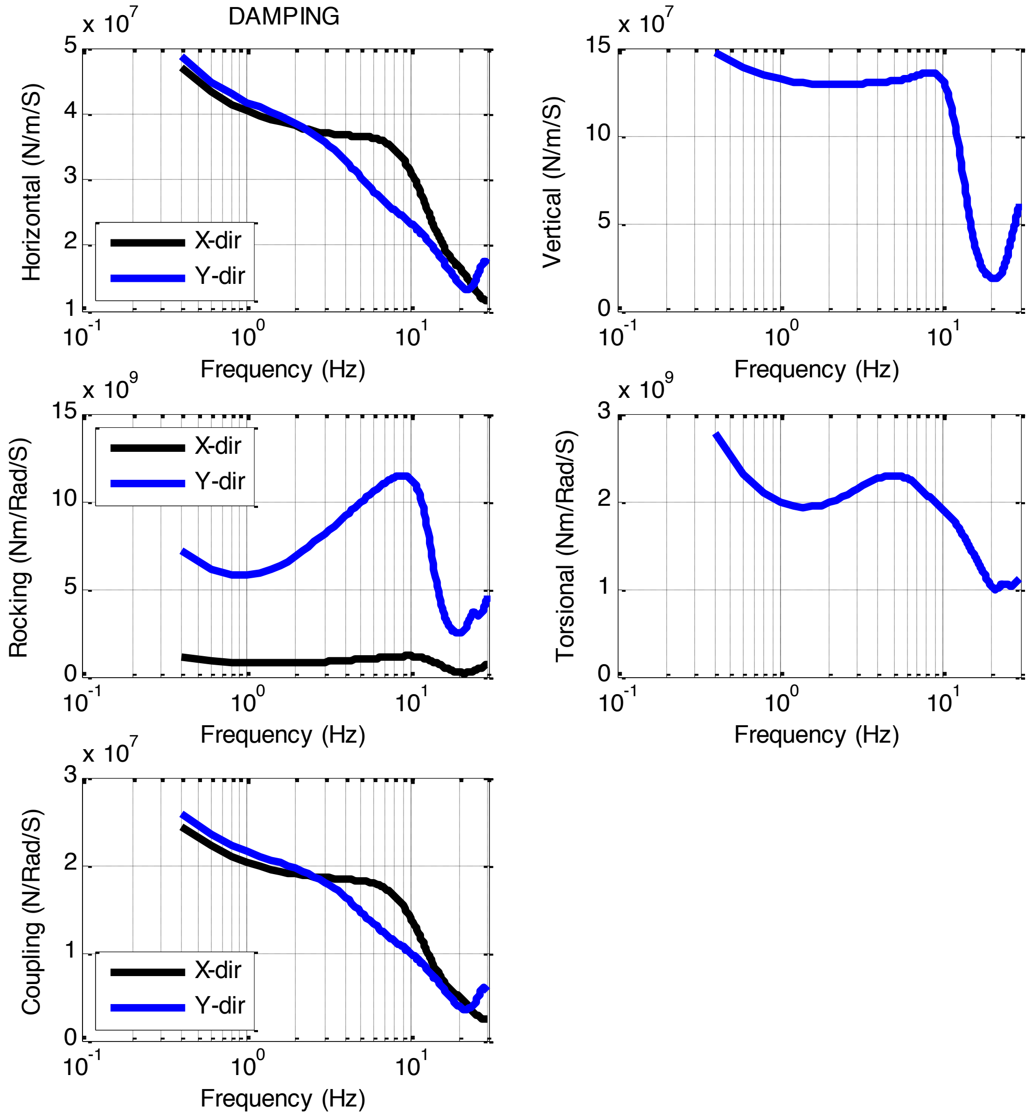


Figure 6.54: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

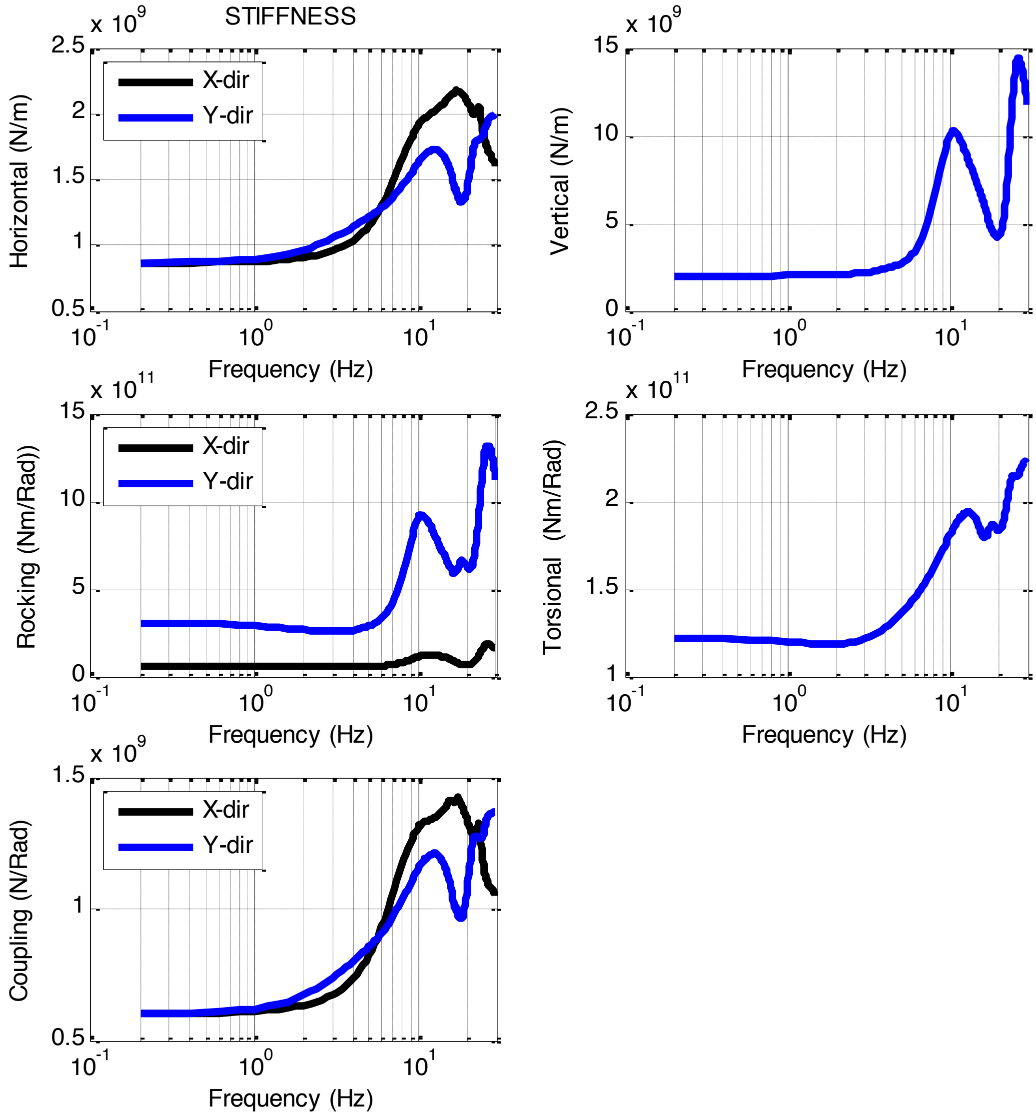


Figure 6.55: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

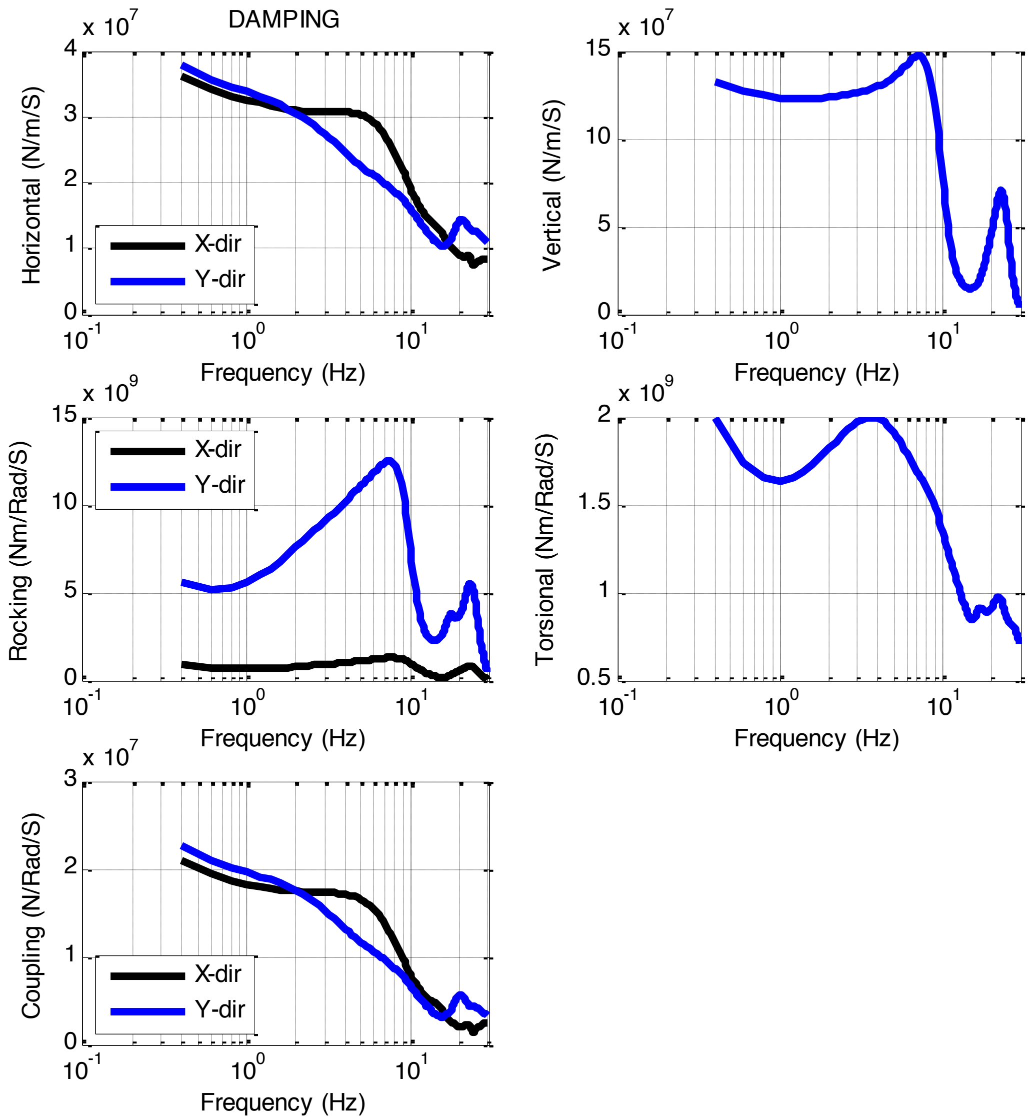


Figure 6.56: Terraced Building with 4 units on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

6.2.2 Pinned head conditions

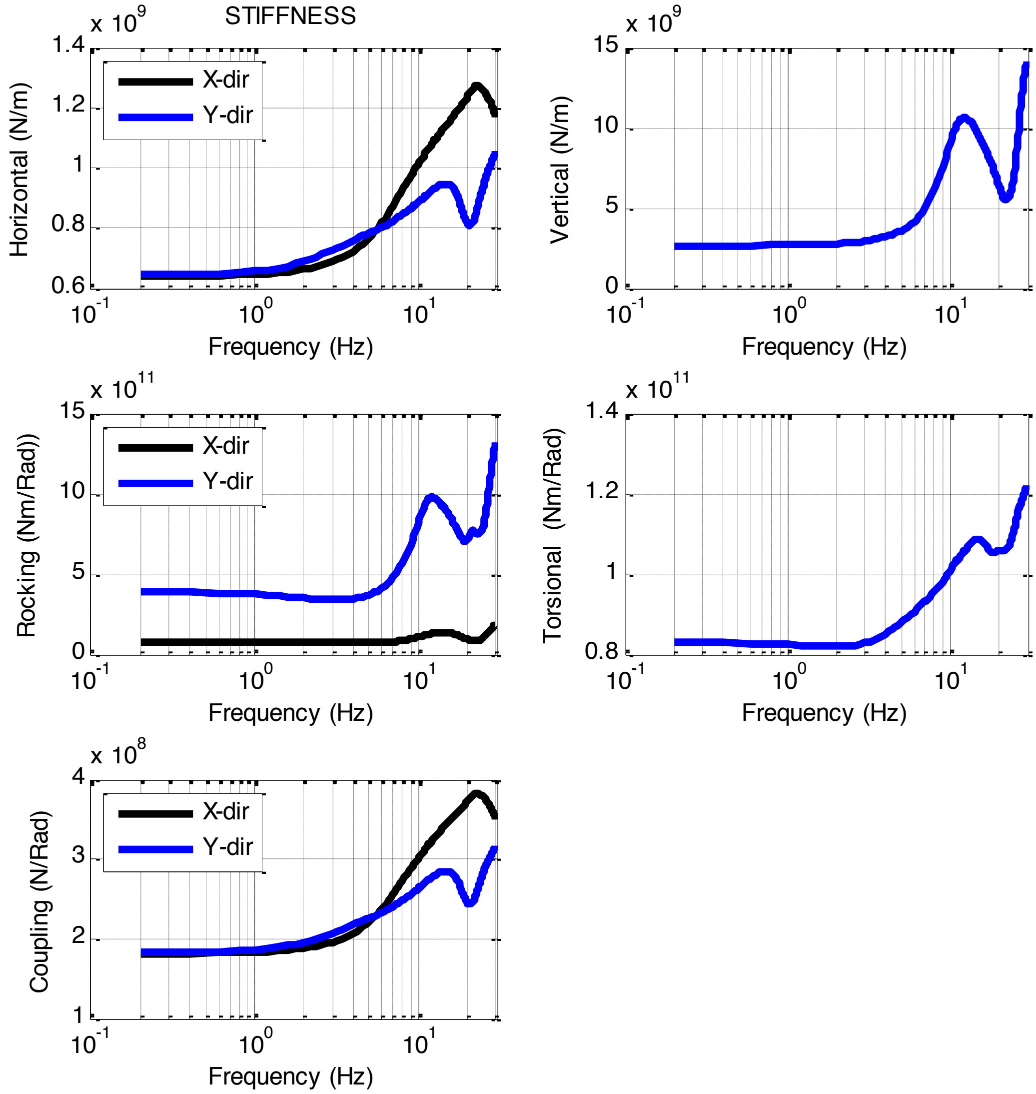


Figure 6.57: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF1: STIFFNESS

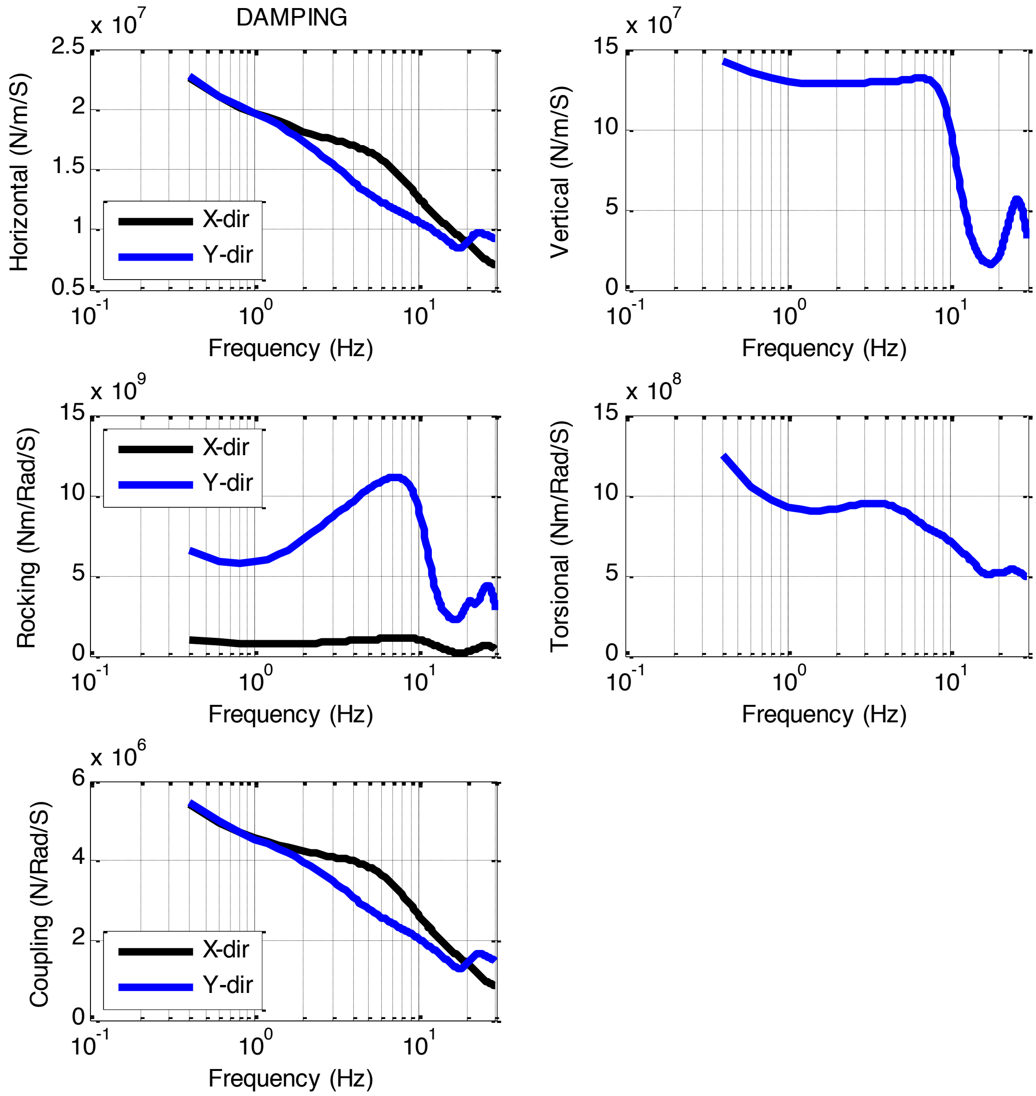


Figure 6.58: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF1: DAMPING

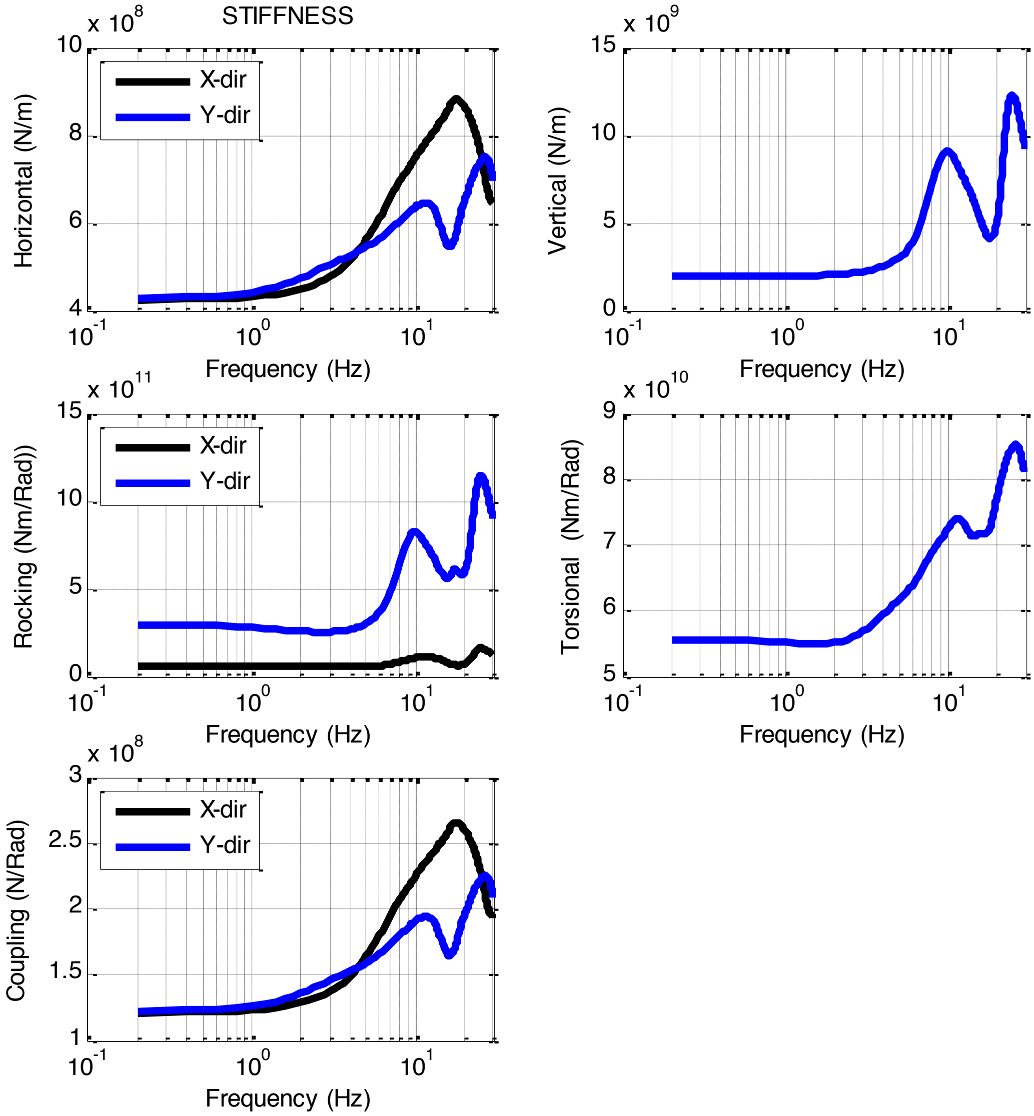


Figure 6.59: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF2: STIFFNESS

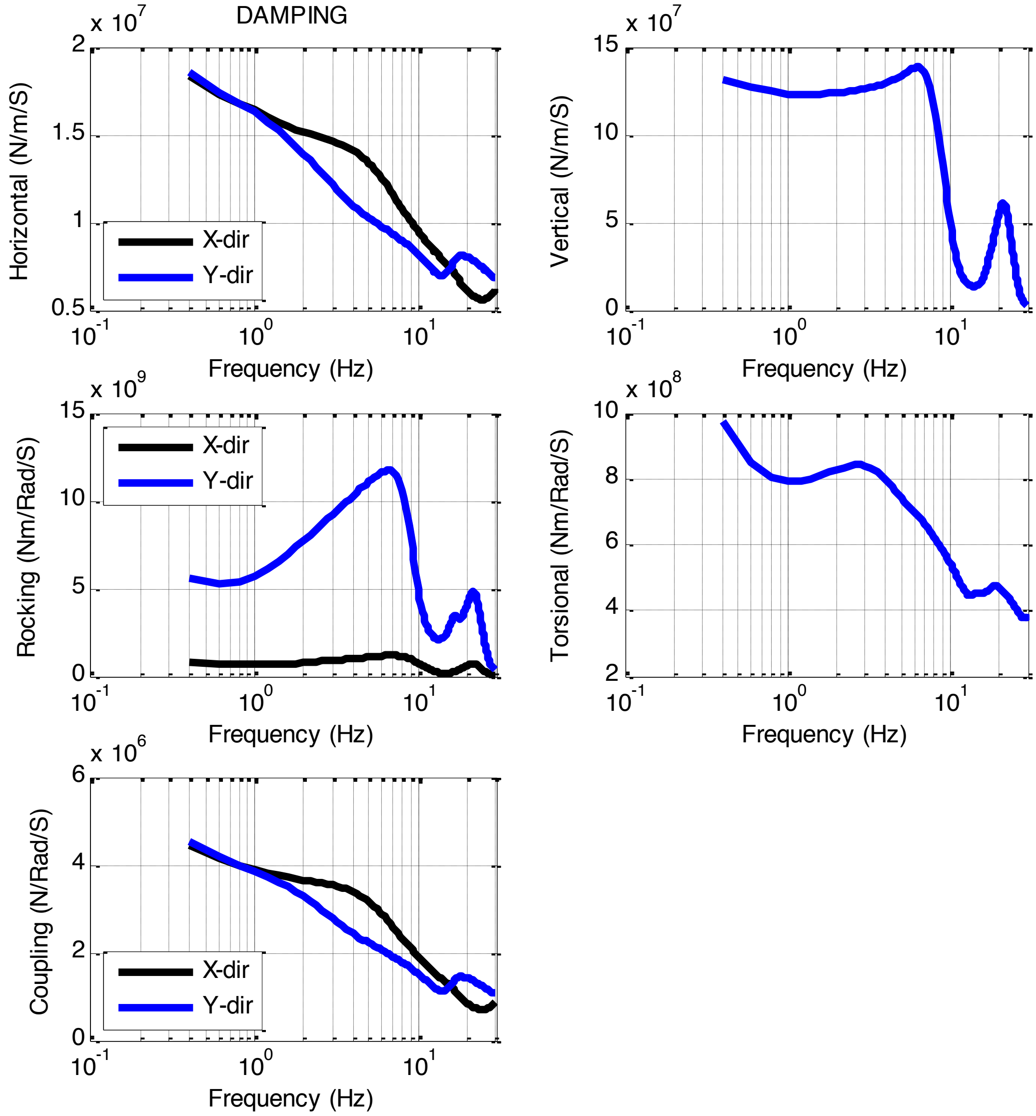


Figure 6.60: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF2: DAMPING

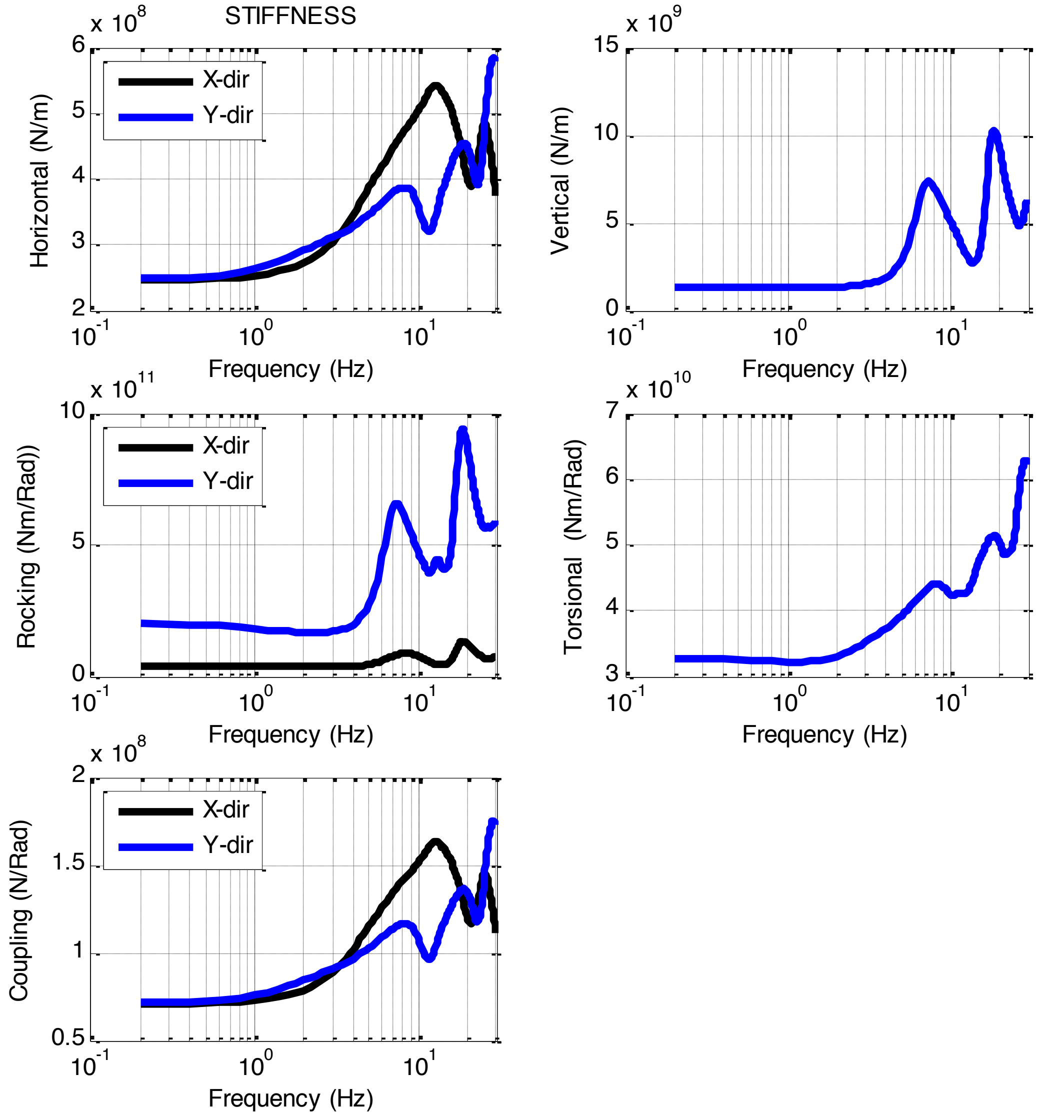


Figure 6.61: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF3: STIFFNESS

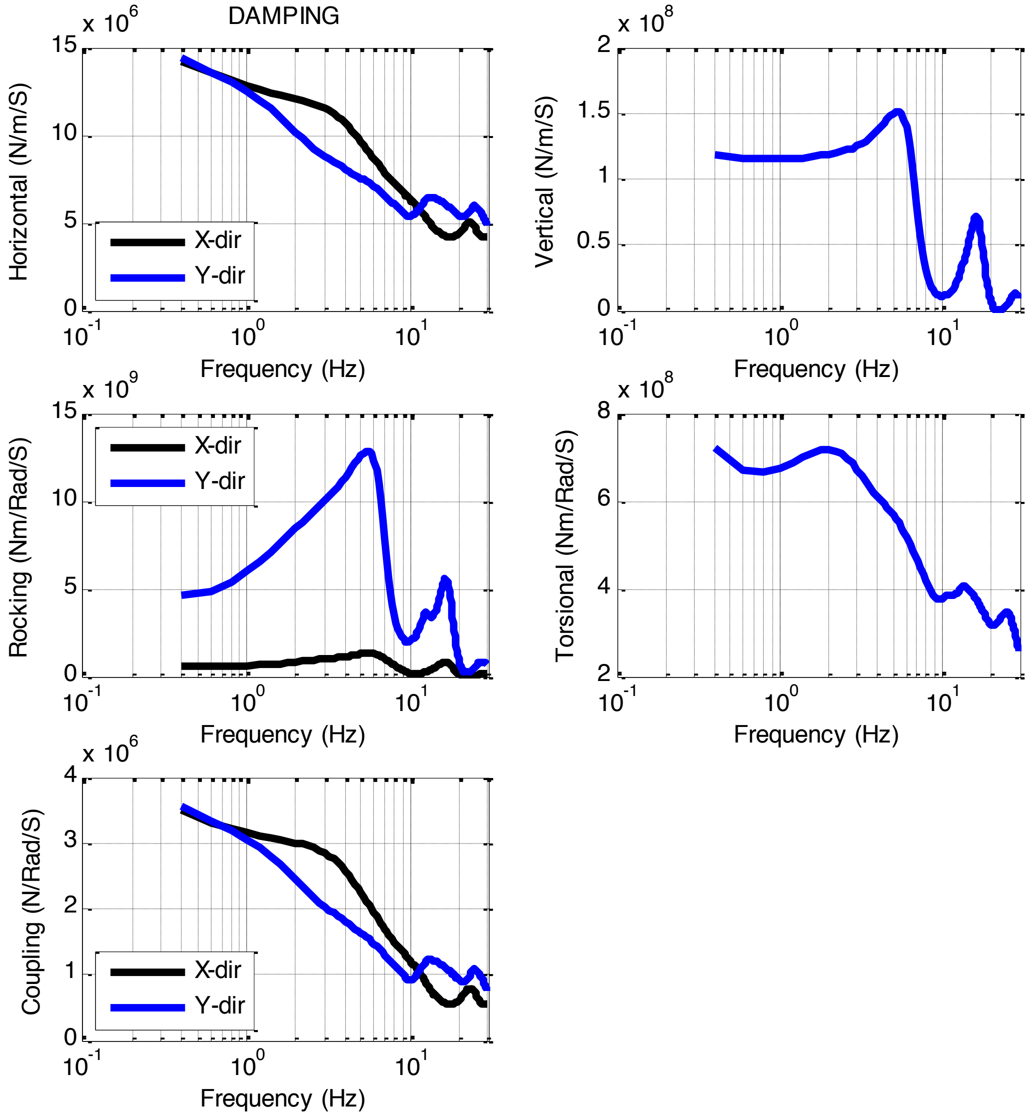


Figure 6.62: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF3: DAMPING

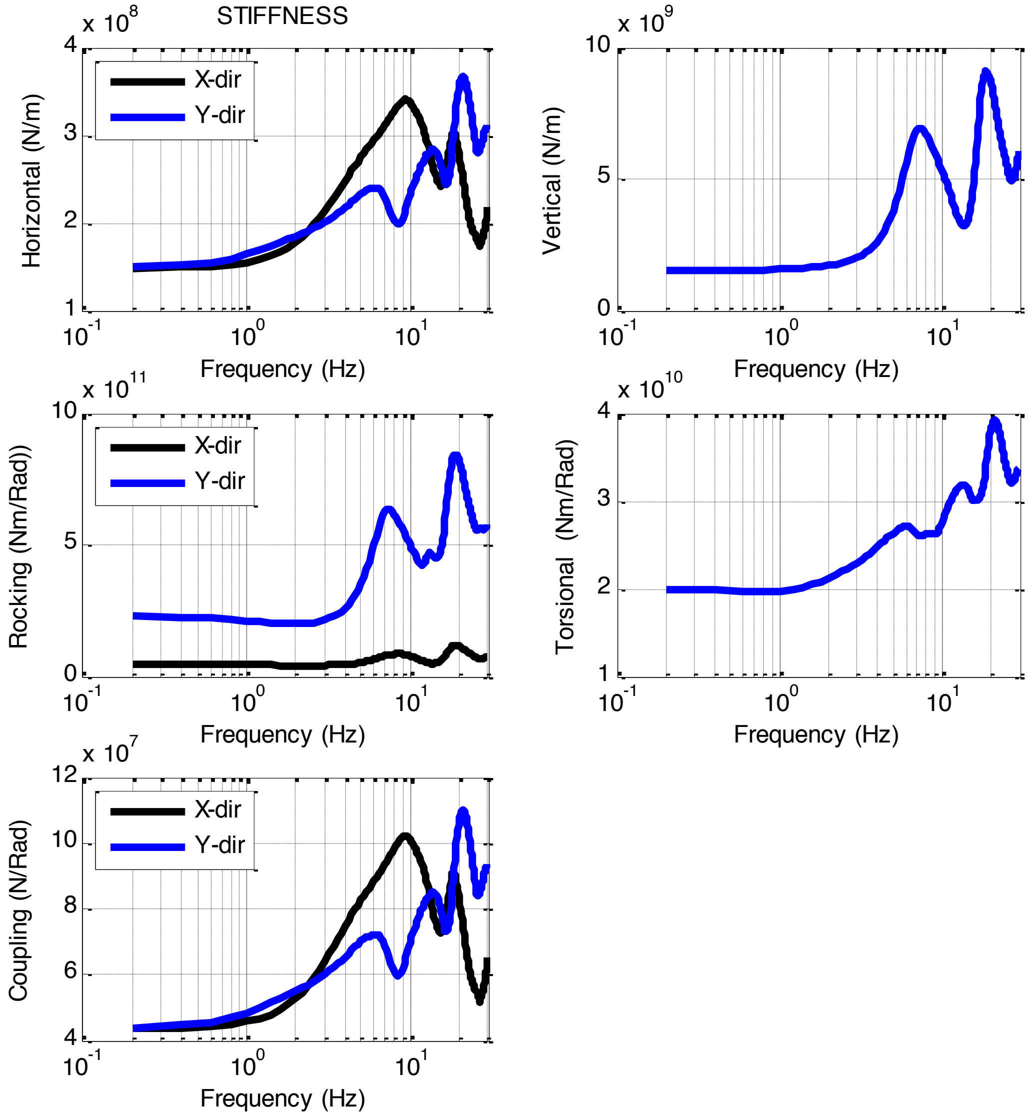


Figure 6.63: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

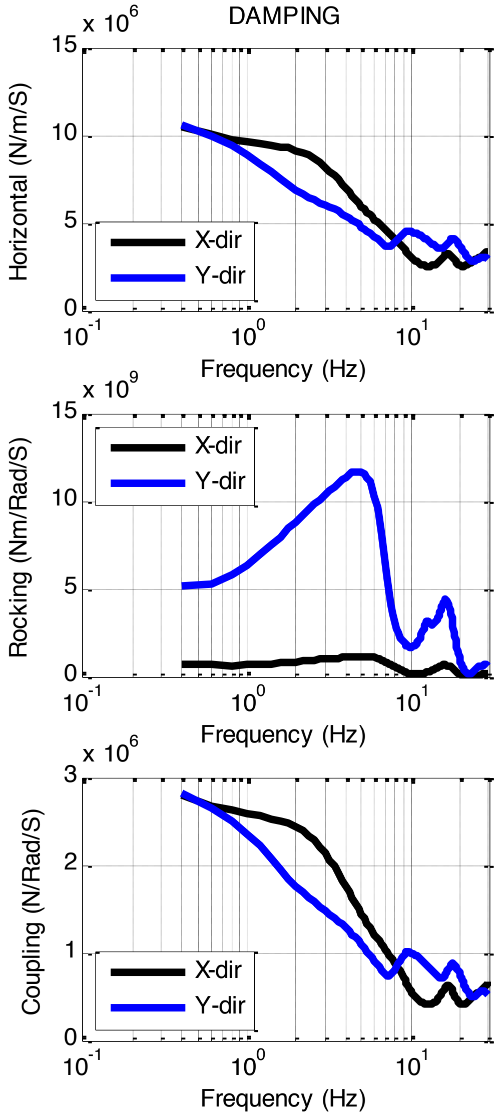


Figure 6.64: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

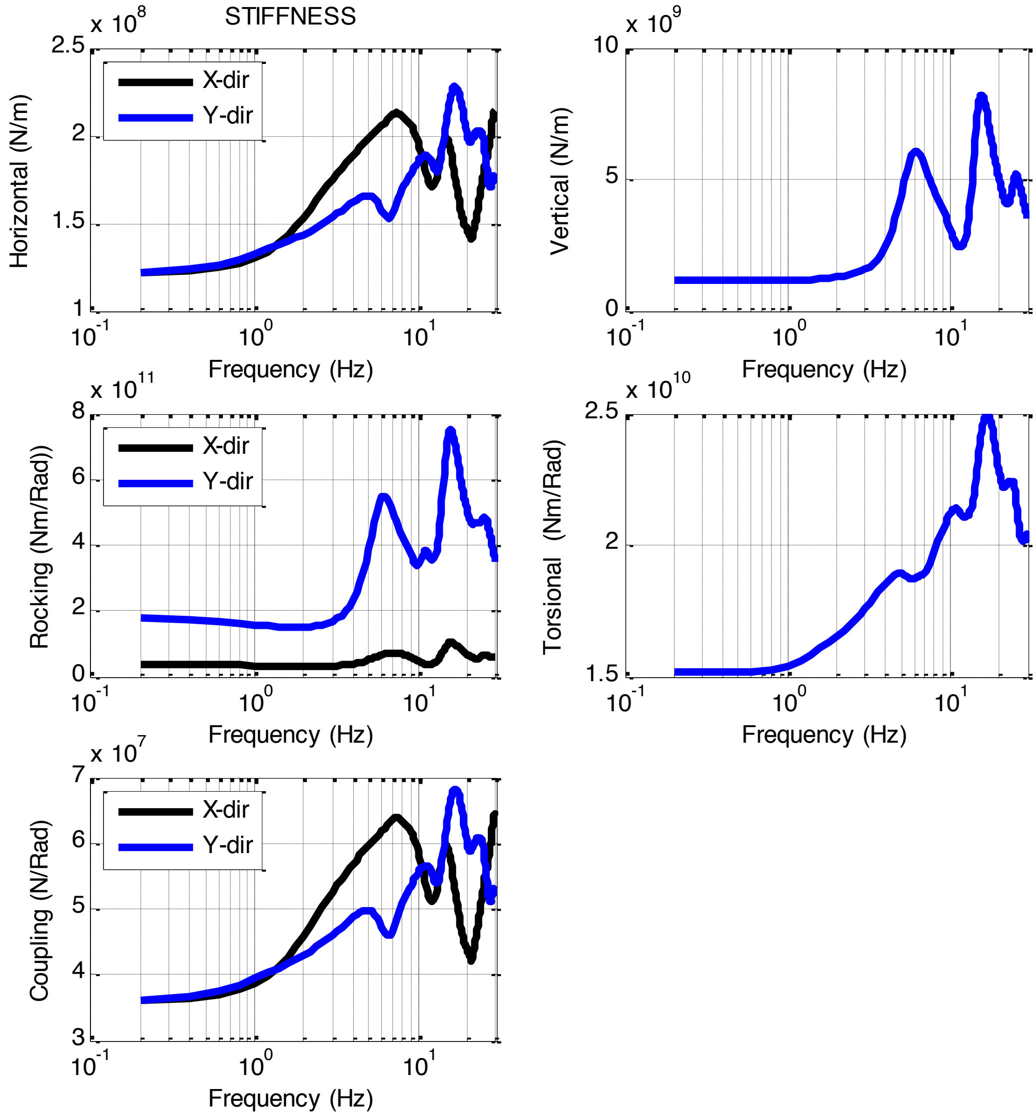


Figure 6.65: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

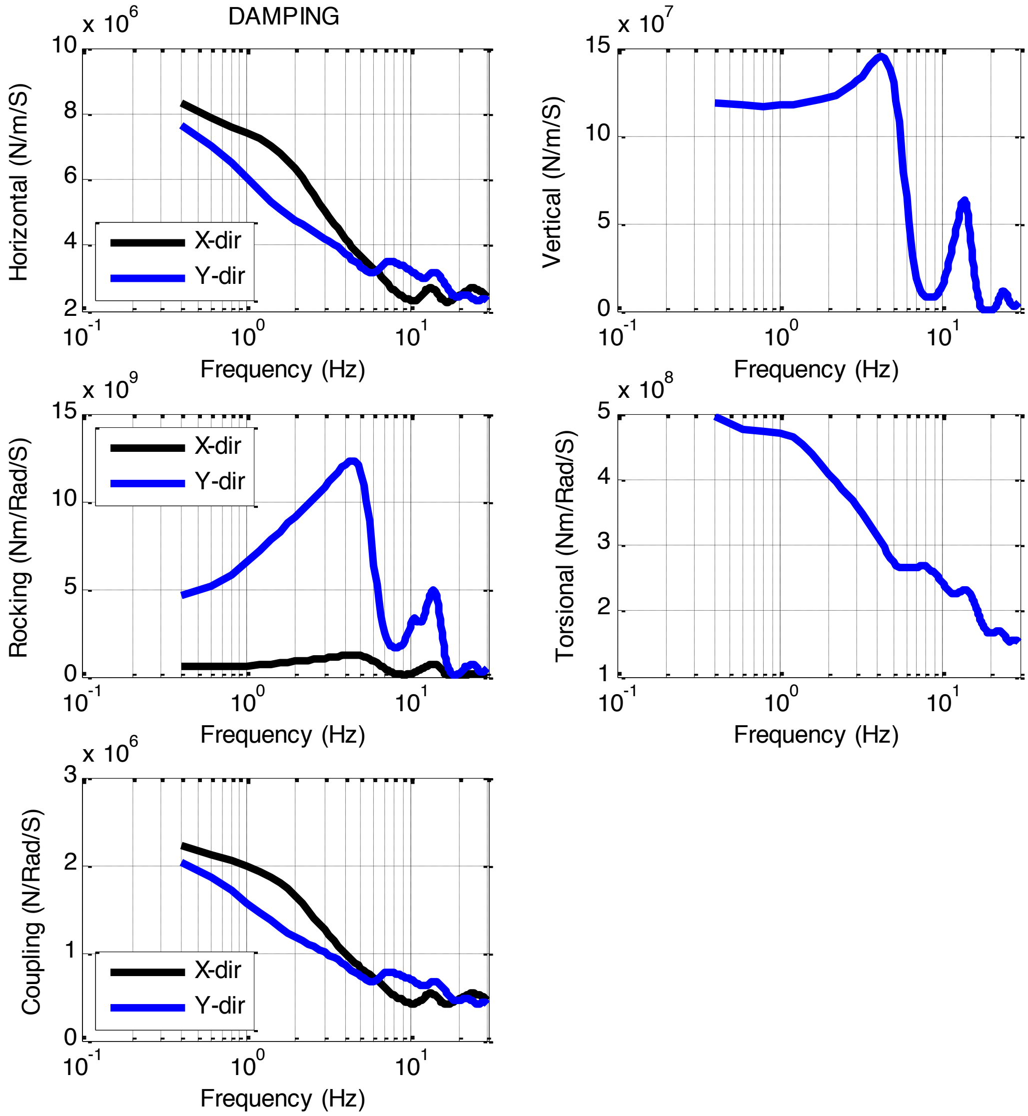


Figure 6.66: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

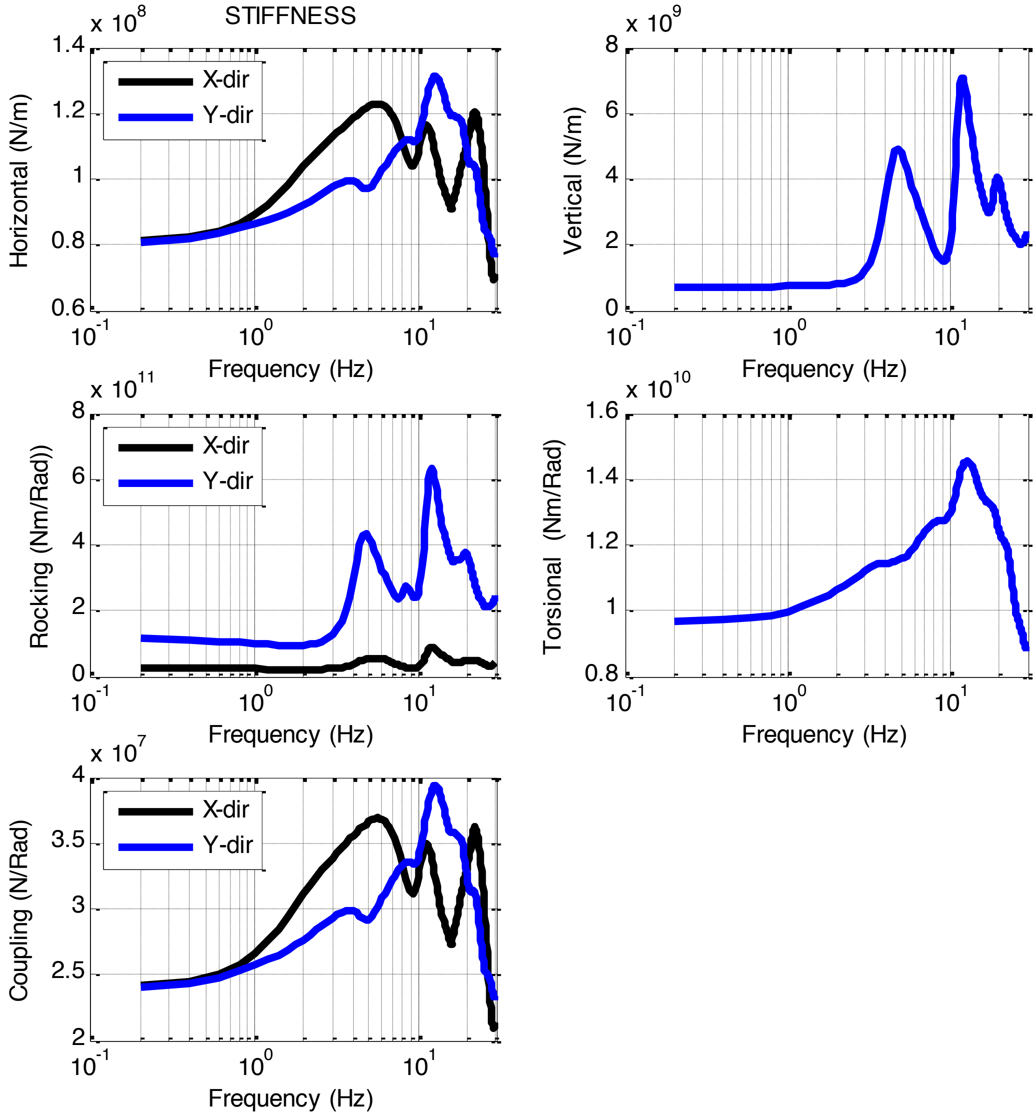


Figure 6.67: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

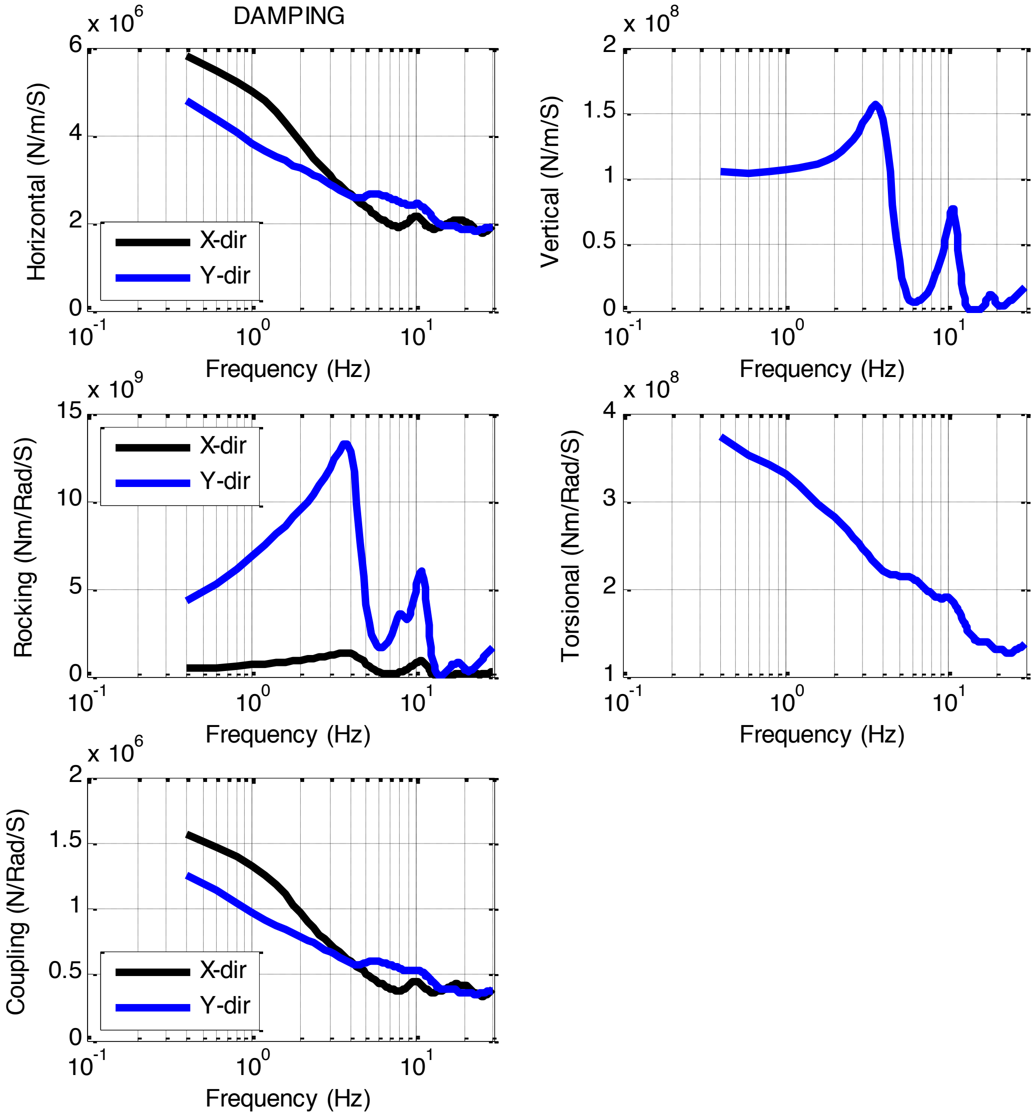


Figure 6.68: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

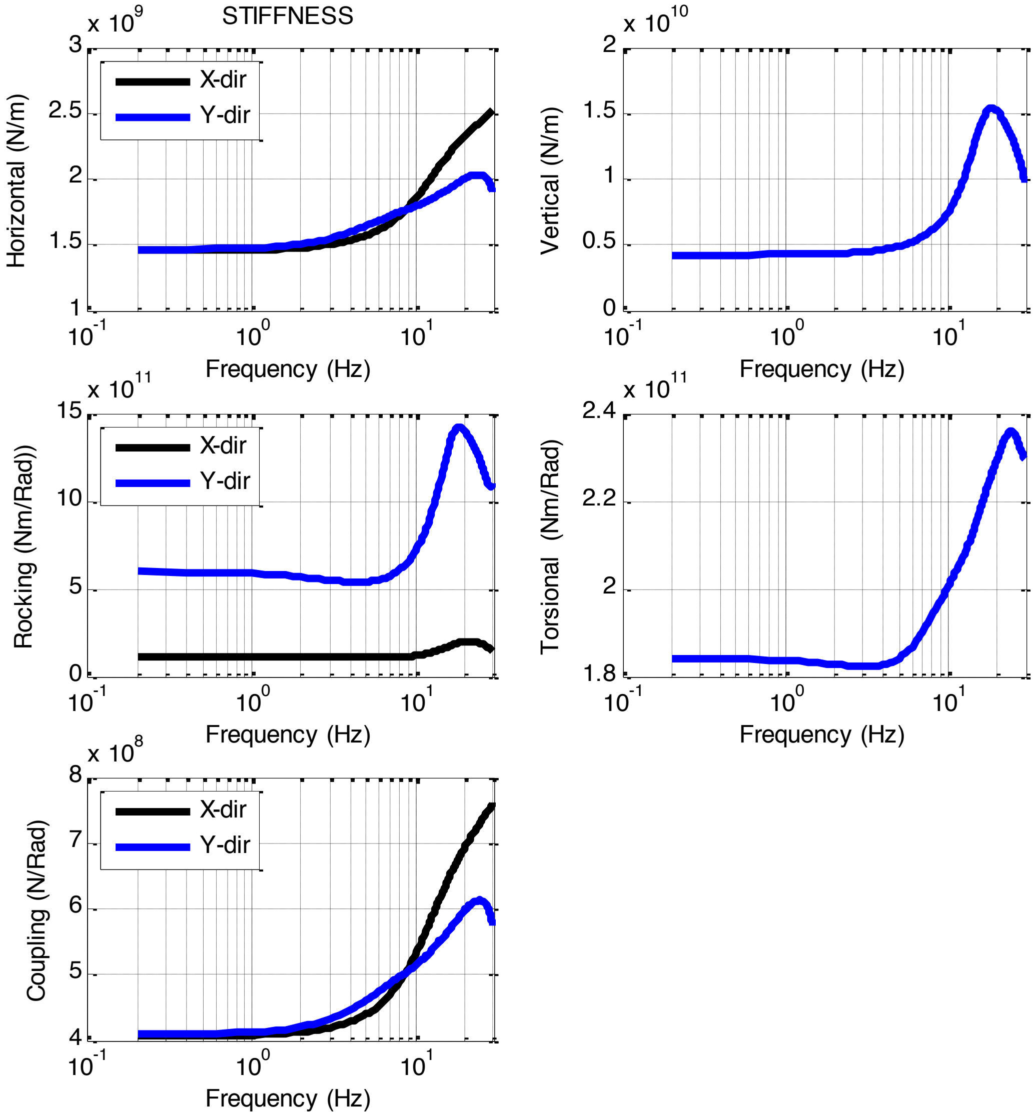


Figure 6.69: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

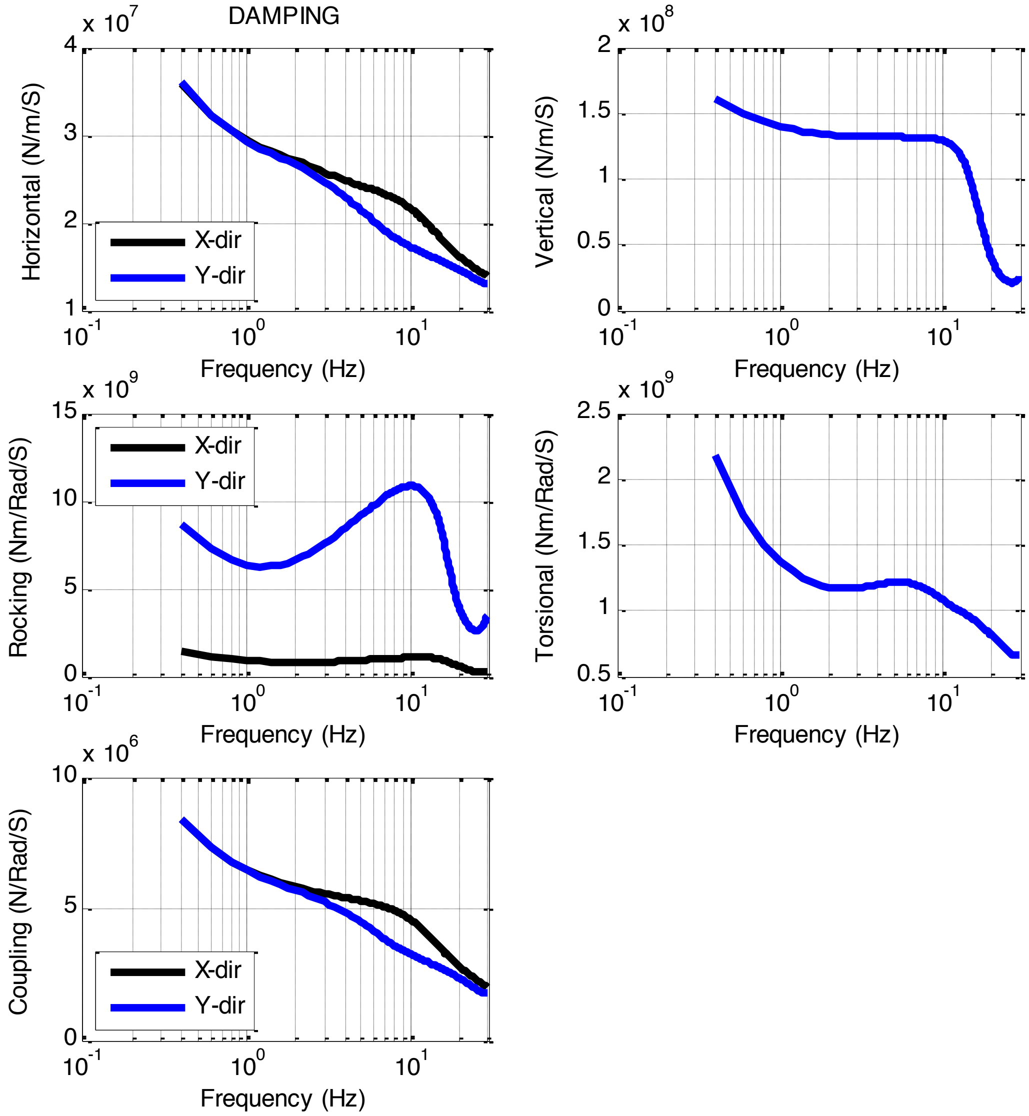


Figure 6.70: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

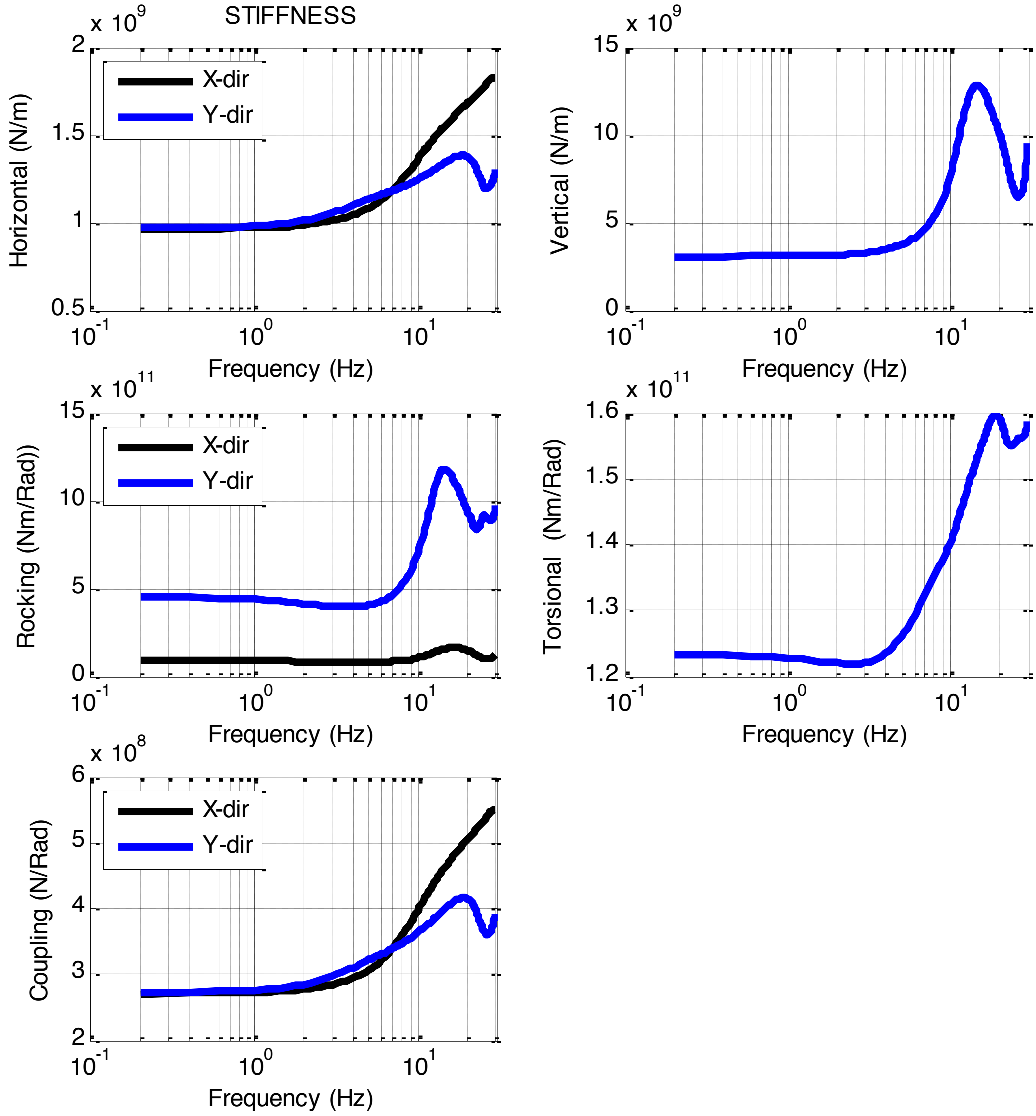


Figure 6.71: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

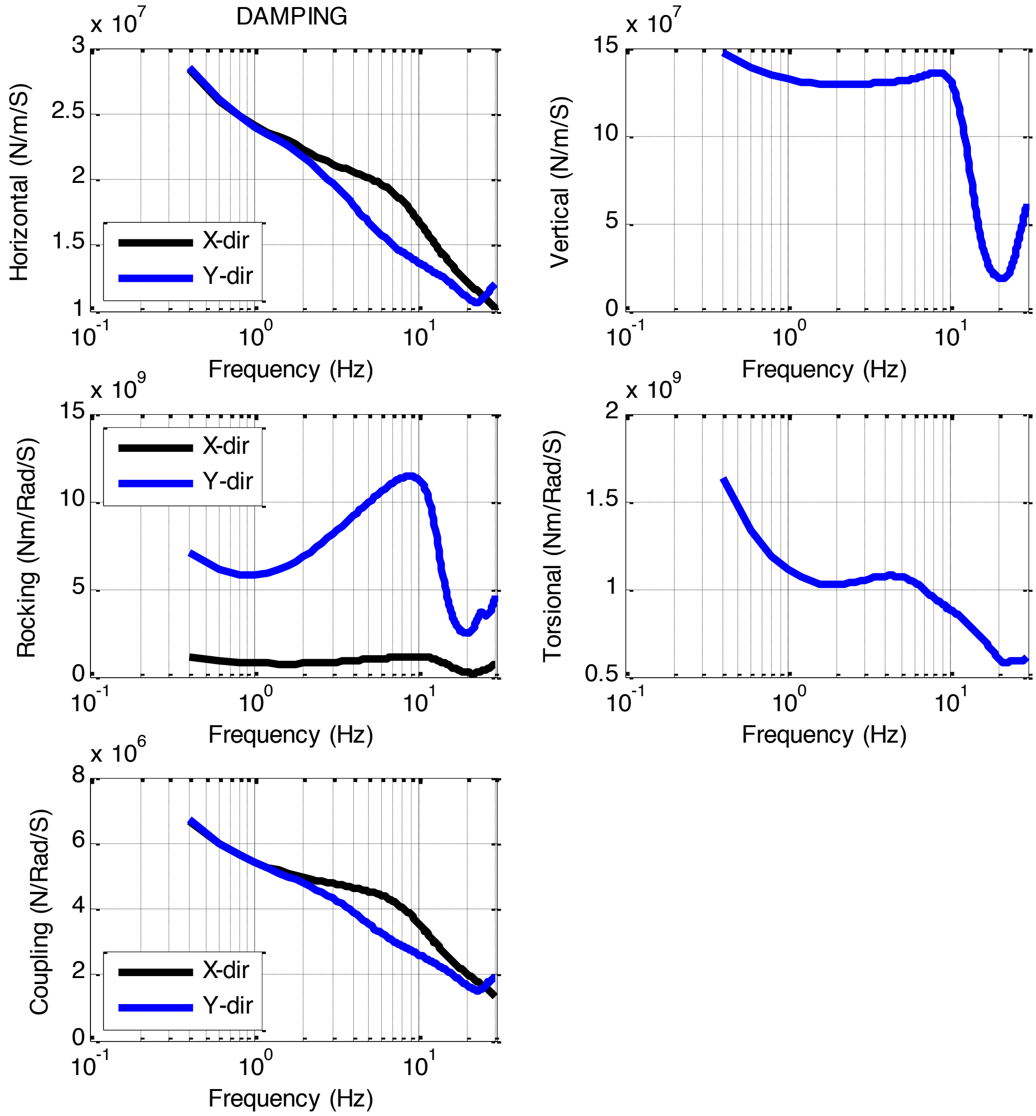


Figure 6.72: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

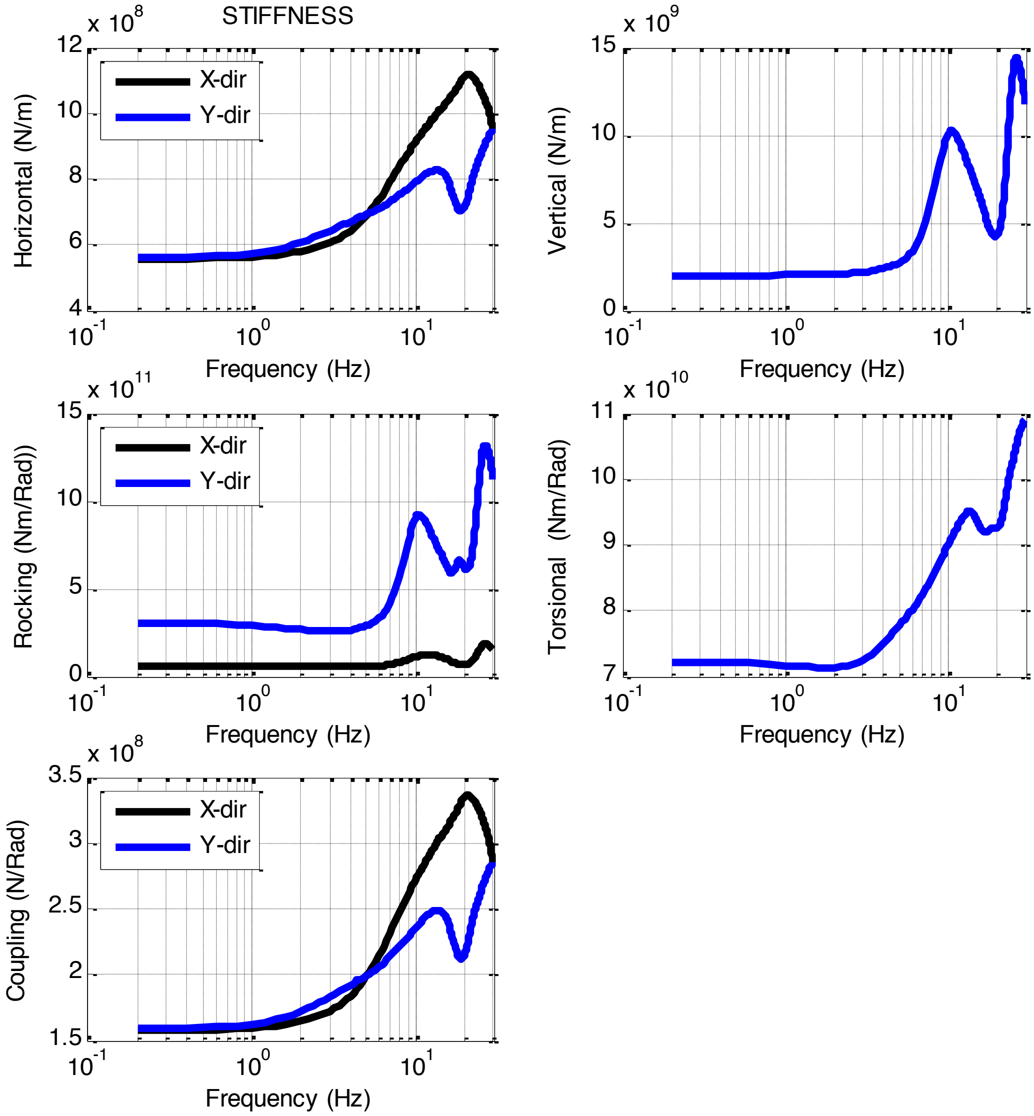


Figure 6.73: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

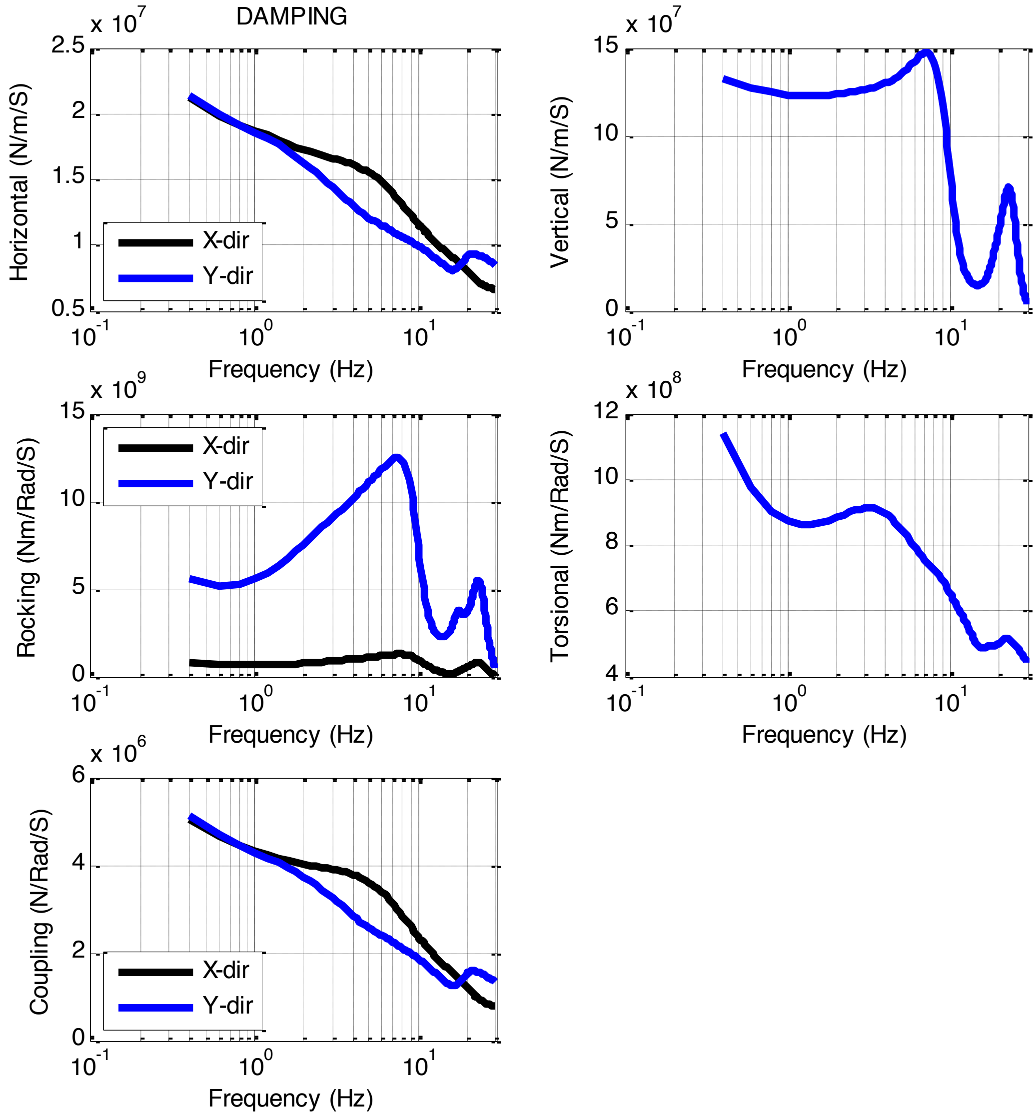


Figure 6.74: Terraced Building with 4 units on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

6.3 Apartment building

Figure 6.75 shows the scheme of the foundations of the Apartment building typology. The following sections, for both fixed and pinned head conditions, shows the impedance functions (in terms of frequency dependent stiffness and damping) of the building taking into account the three reference soil profiles defined in section 4.1.1 and the three scaling factors of section 4.1.2. The characteristics of the cap foundations are summarized in the following table. The foundation consists of a solid circular 450 mm diameter section concrete piles ($A=0.2025m^2$; $I_{xx}=I_{yy}=0.003417m^4$; $I_{zz}=0.006834m^4$). The pile length considered is equal to 16m.

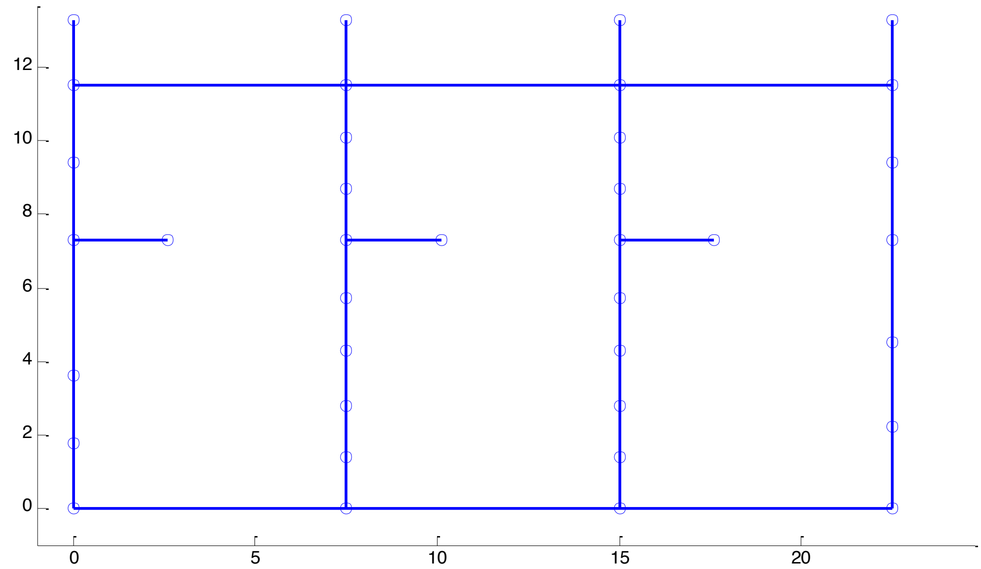


Figure 6.75: Apartment building: schematic position of beam foundations and location of piles

Table 6.3: Foundations characteristics of Apartment building

Foundation dimensions							Mass moment of inertia					
L_x [m]	L_y [m]	H [m]	A [m²]	$D_{eq,x}$ [m]	$D_{eq,y}$ [m]	m [kg]	I_{xx} [kg m²]	I_{yy} [kg m²]	I_{zz} [kg m²]	I_{xy} [kg m²]	I_{xz} [kg m²]	I_{yz} [kg m²]
22.5	12	0.45	51.6	10.05	5.14	77.4e3	1539.2e3	4562.0e3	6096.5e3	-12.7e3	0	0

6.3.1 Fixed head conditions

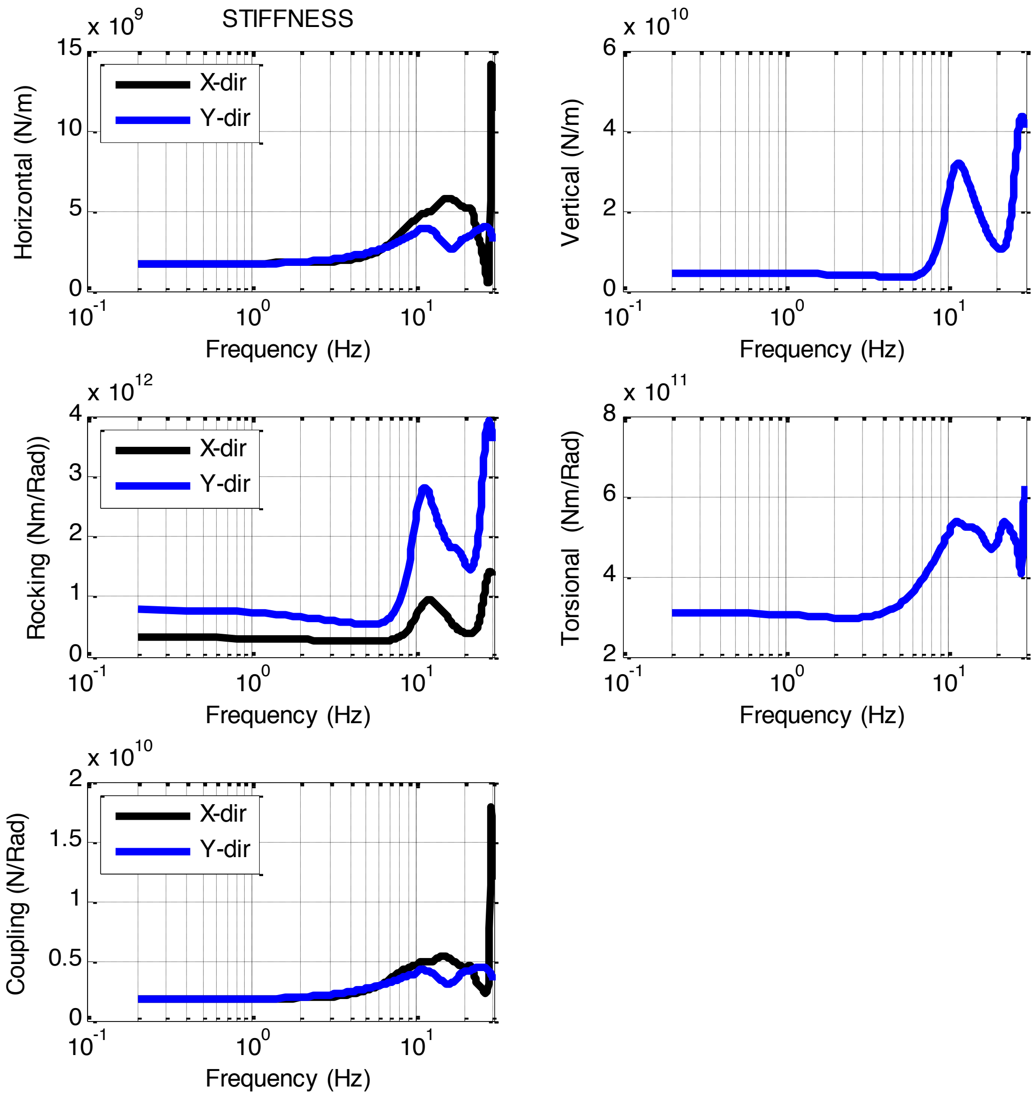


Figure 6.76: Apartment Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF1: STIFFNESS

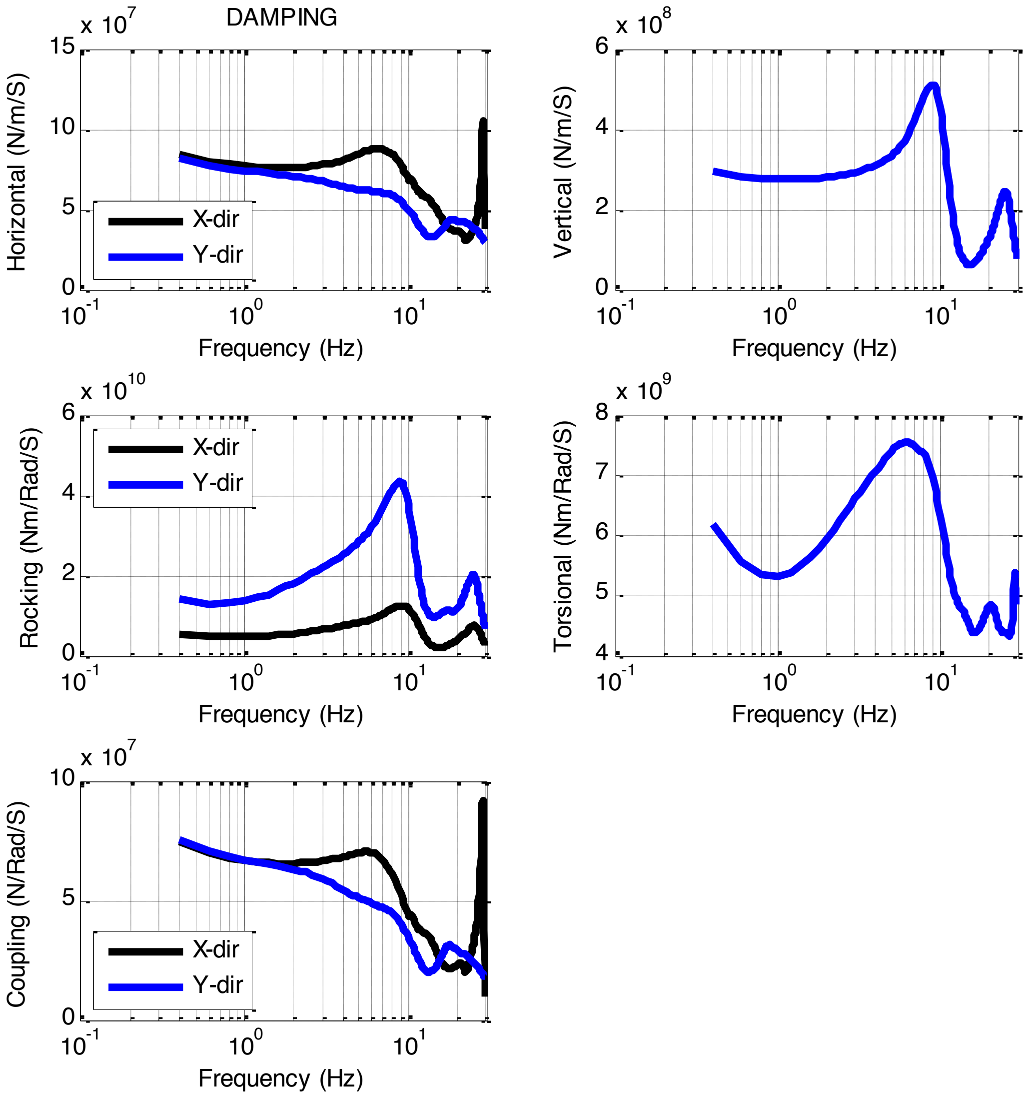


Figure 6.77: Apartment Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF1: DAMPING

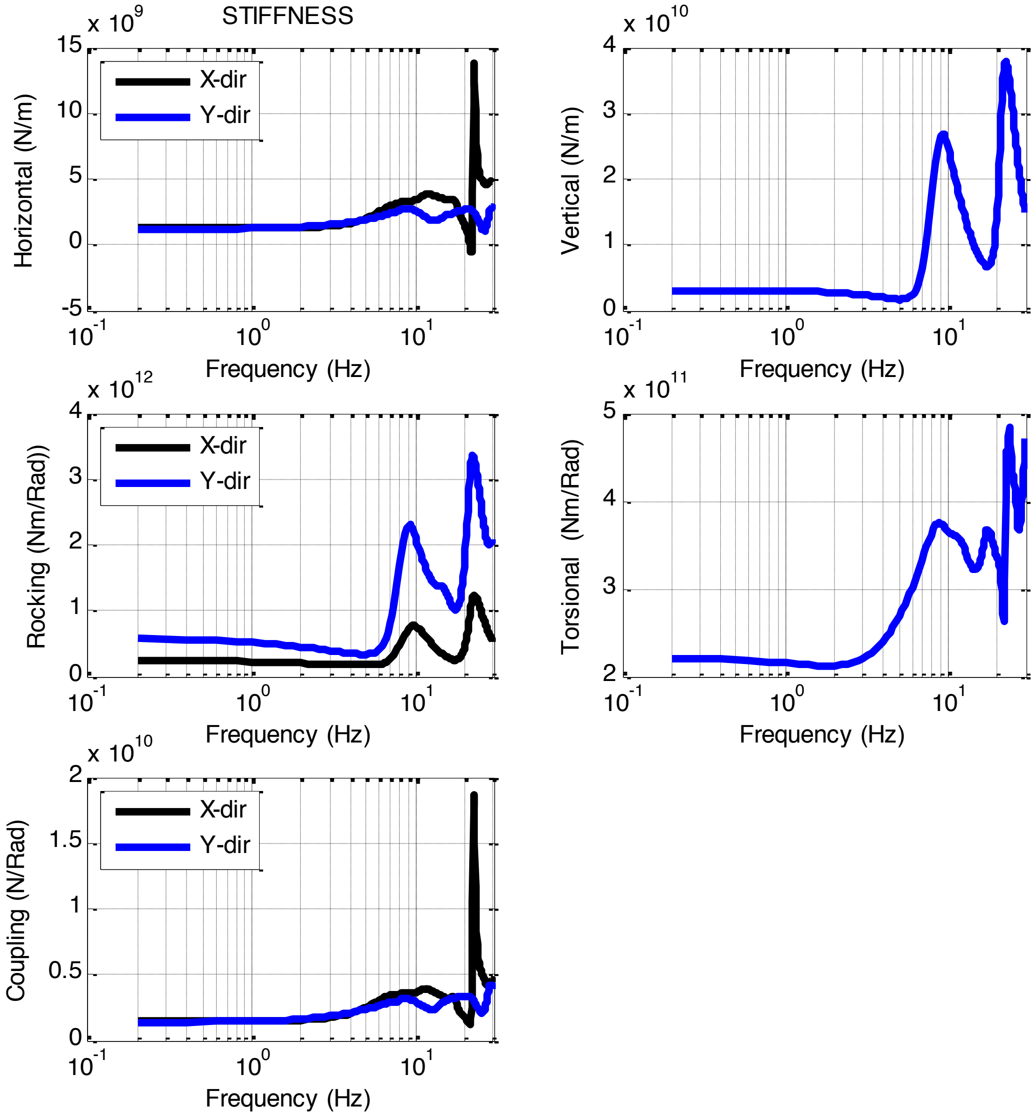


Figure 6.78: Apartment Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF2: STIFFNESS

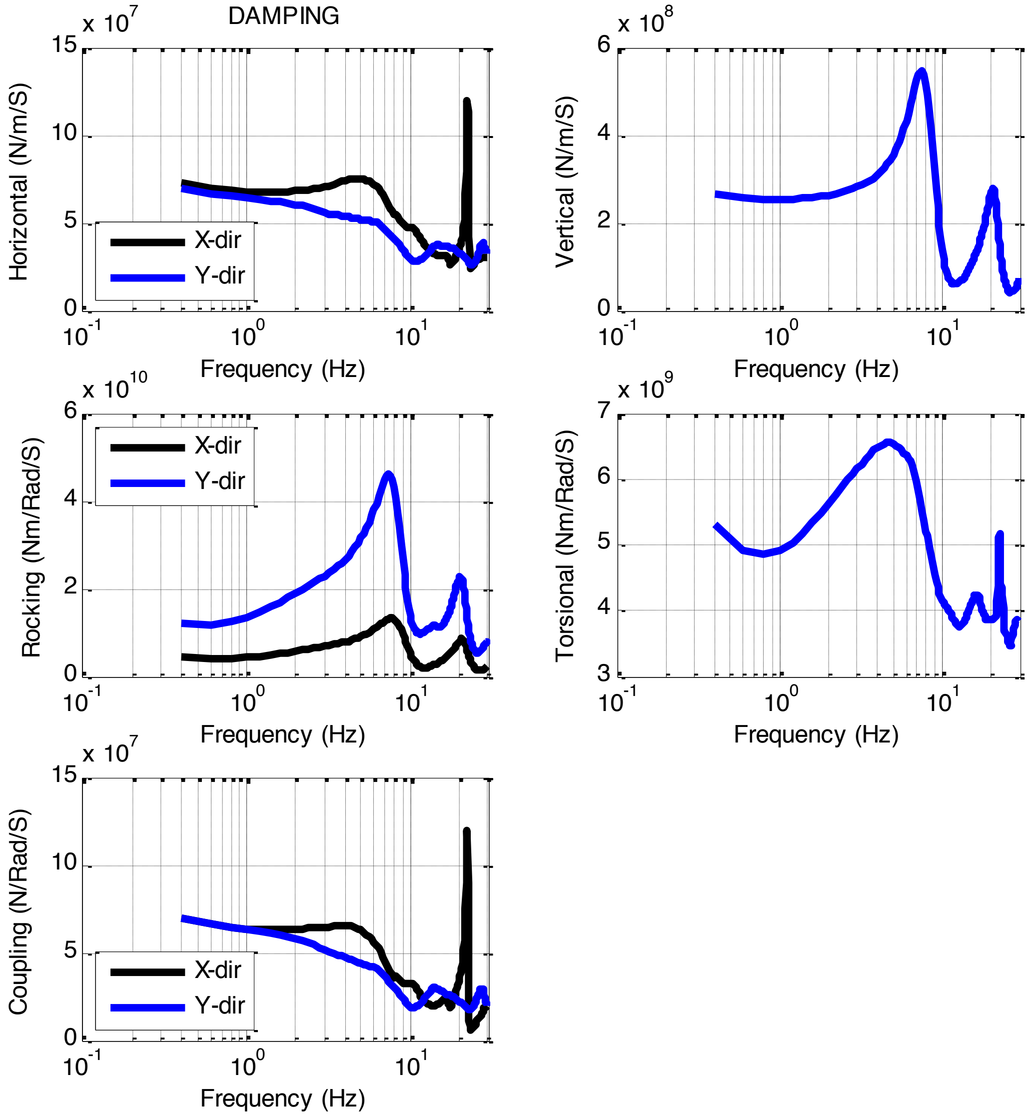


Figure 6.79: Apartment Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF2: DAMPING

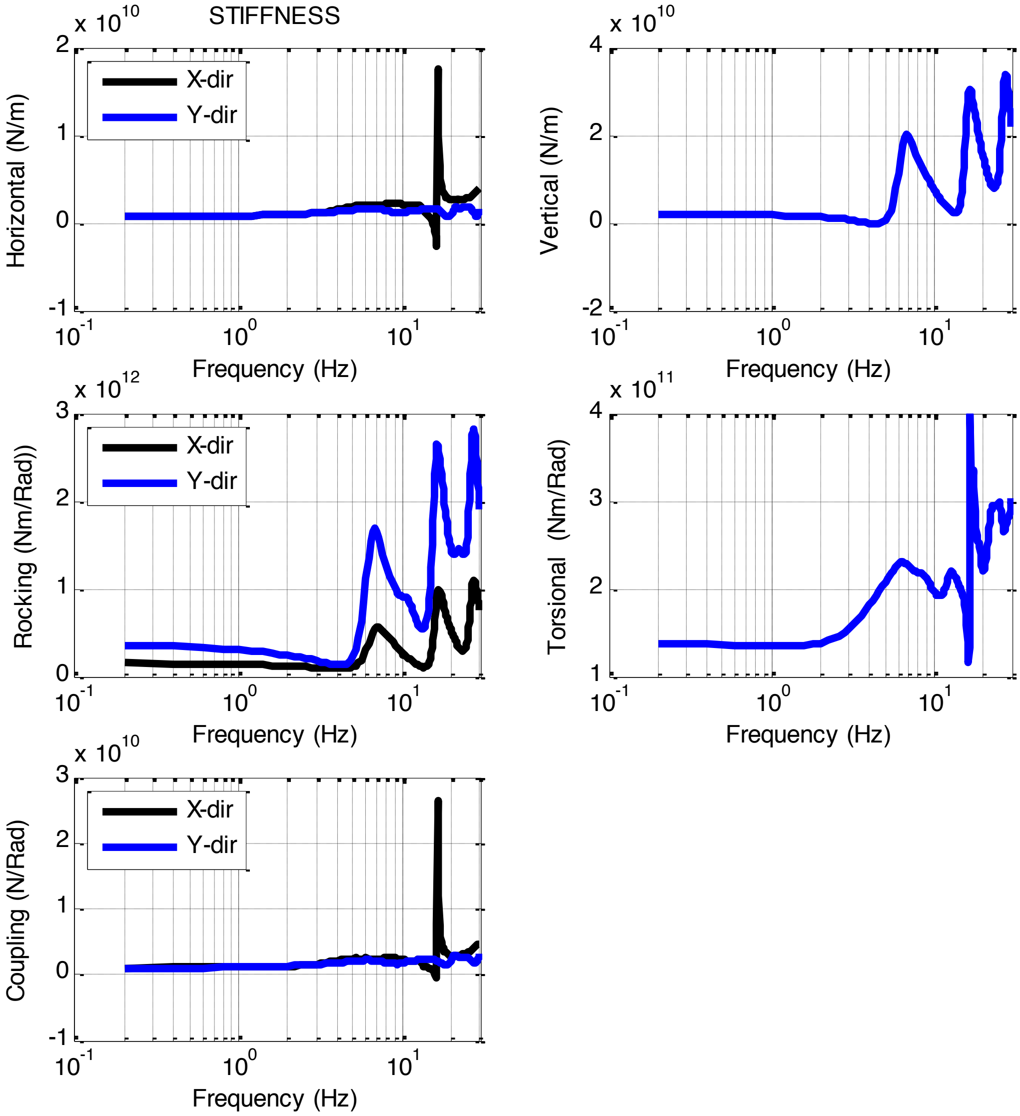


Figure 6.80: Apartment Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF3: STIFFNESS

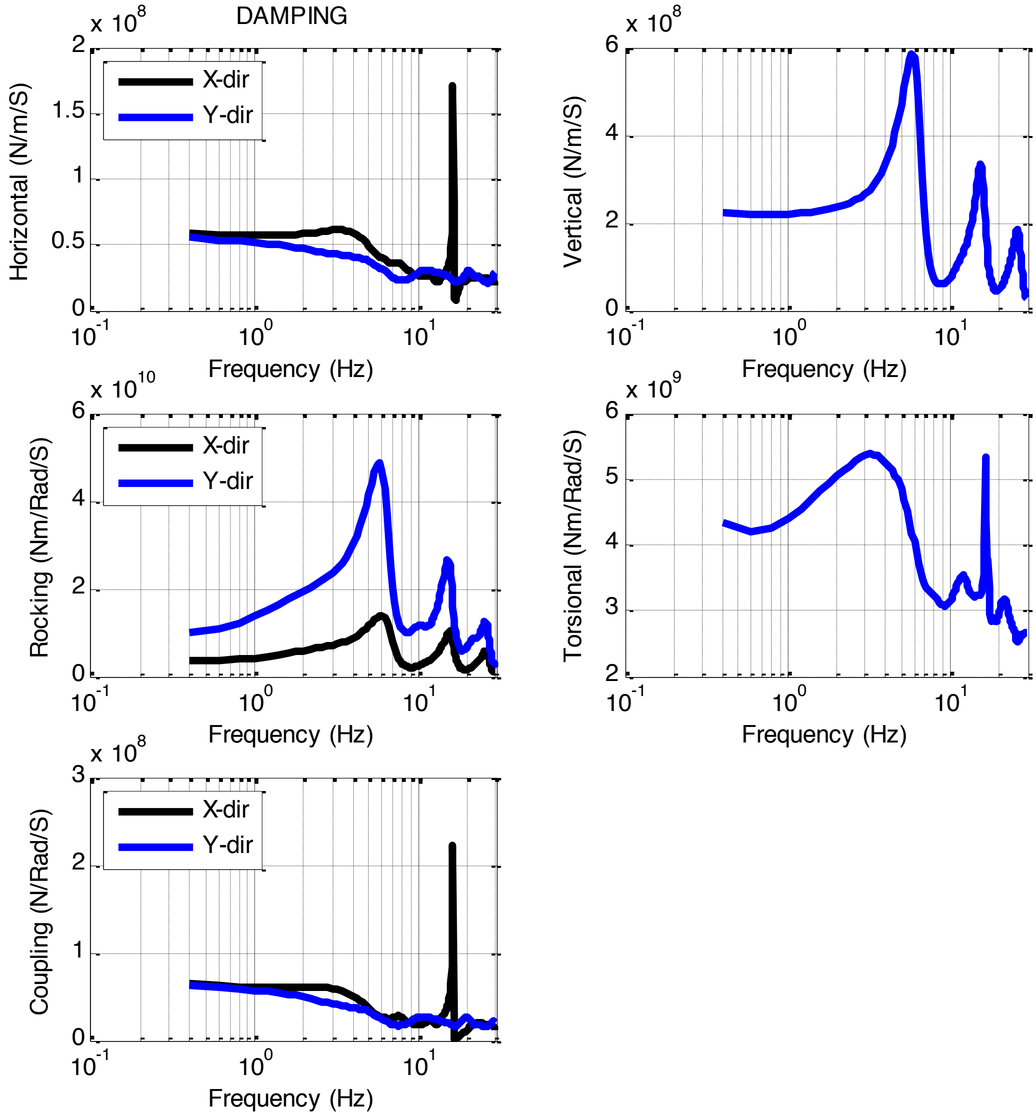


Figure 6.81: Apartment Building on deep foundations – Fixed head conditions – Mean V_S profile with scaling factor SF3: DAMPING

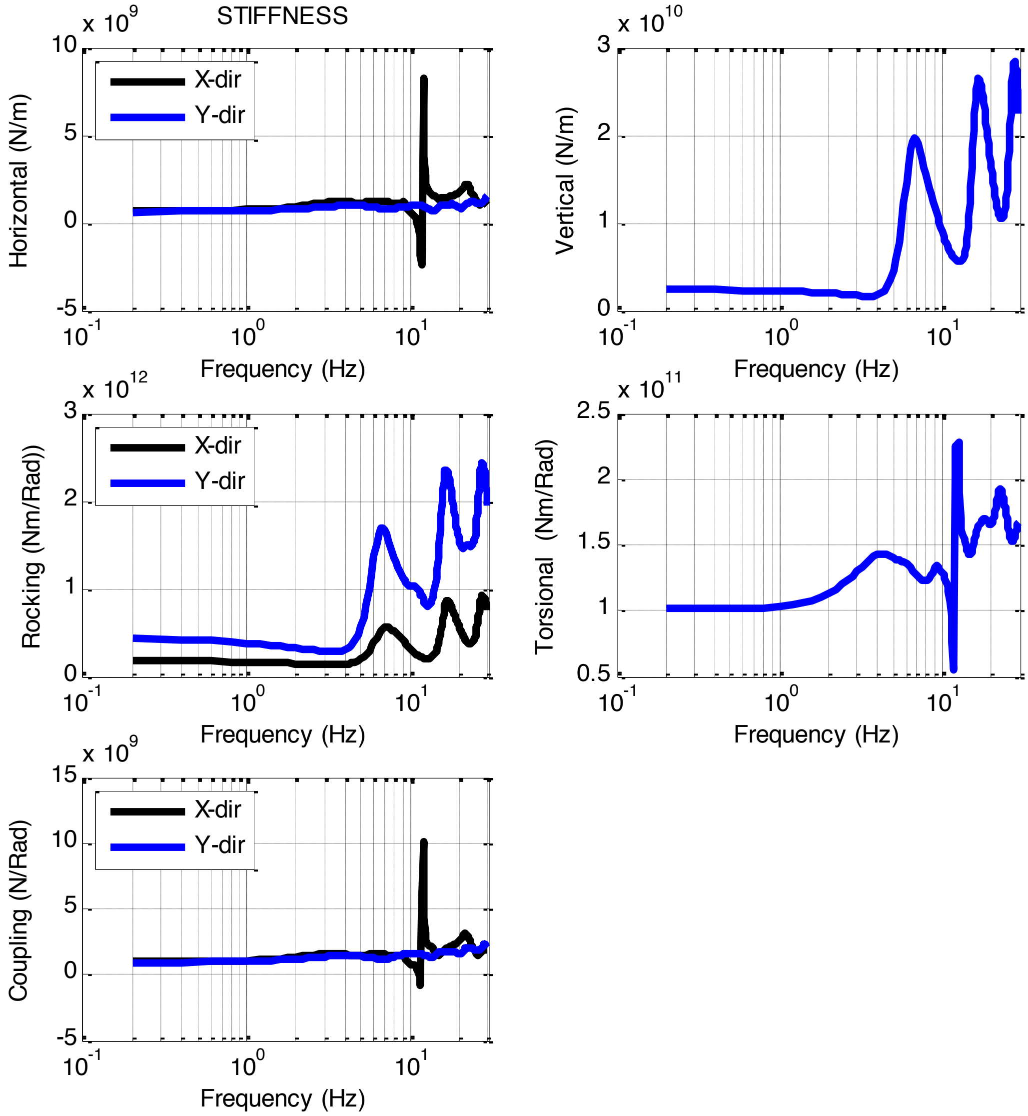


Figure 6.82: Apartment Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

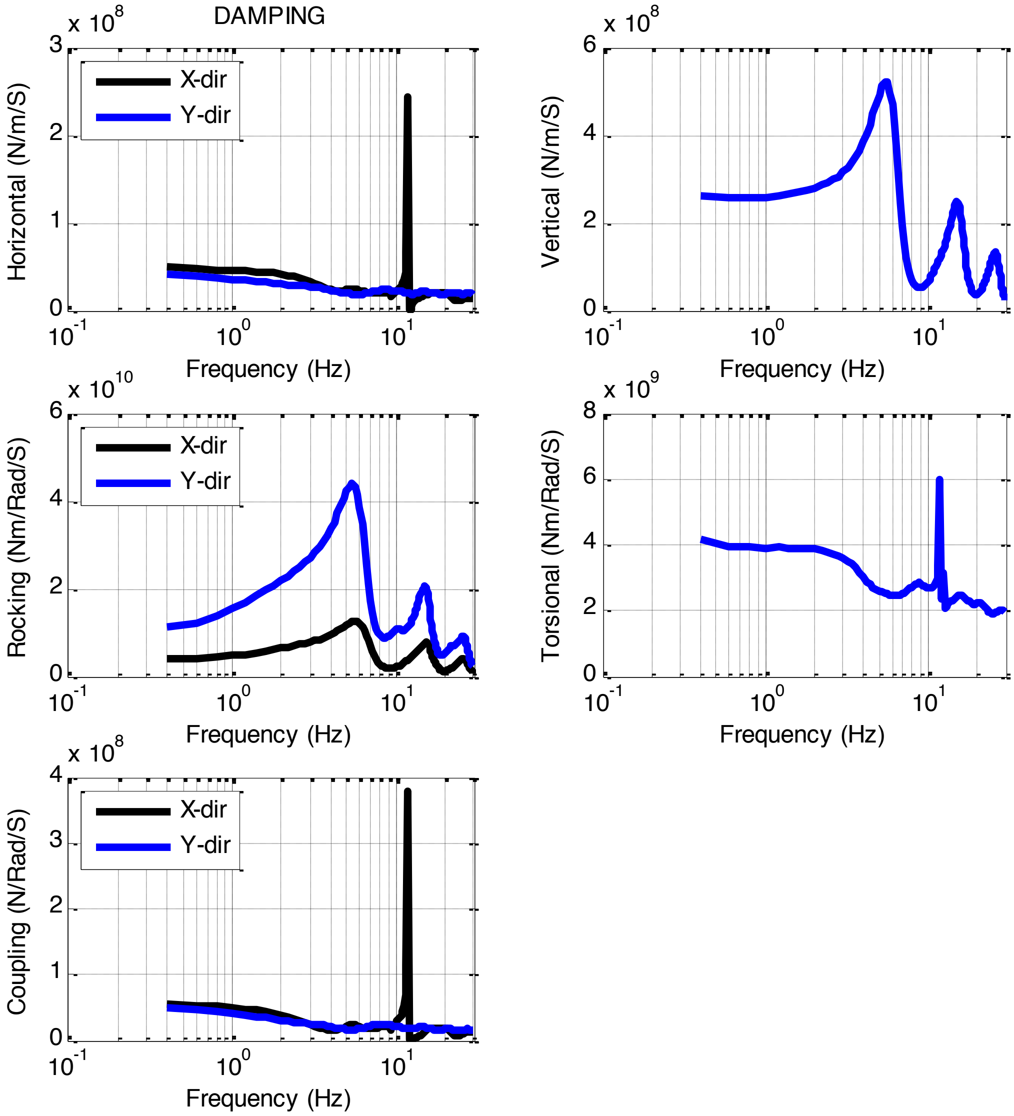


Figure 6.83: Apartment Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

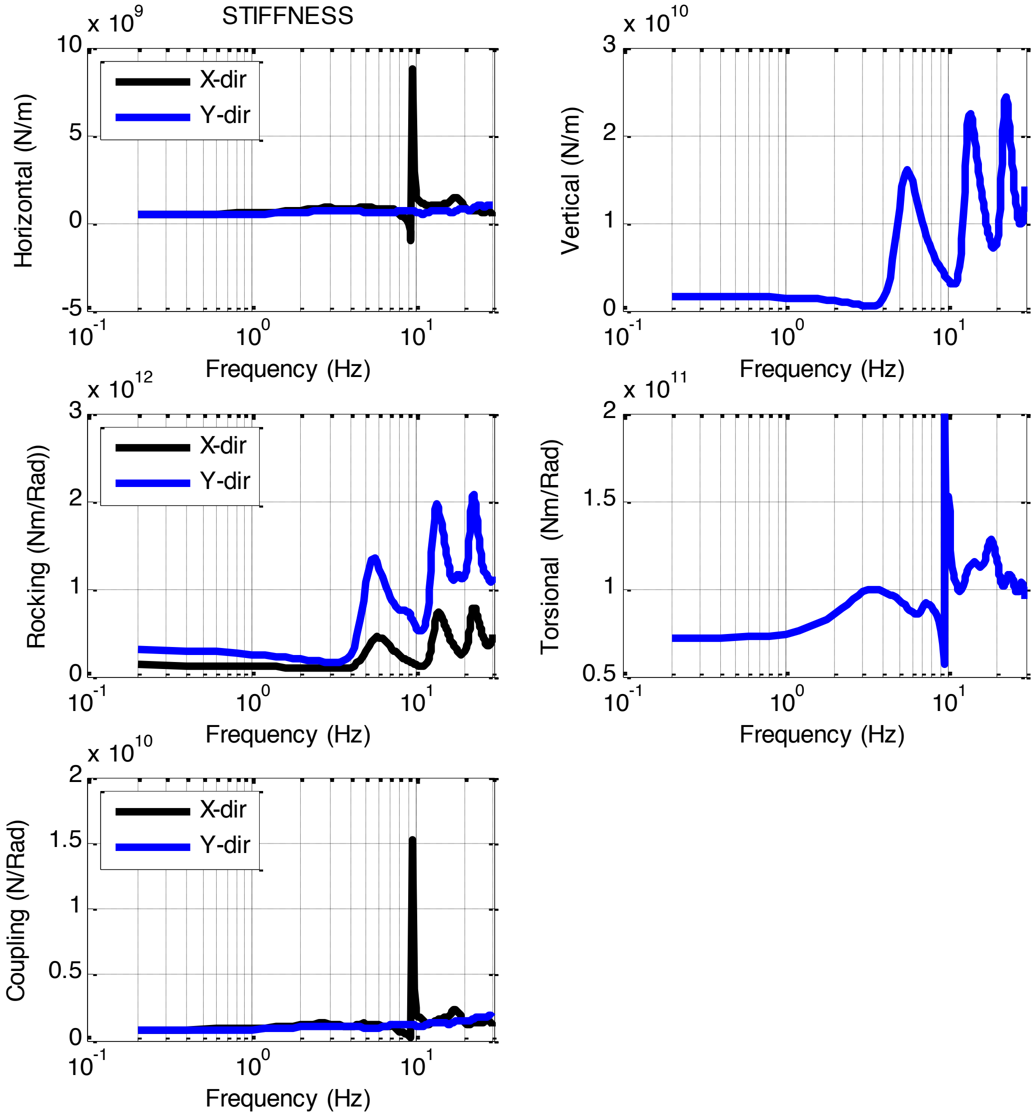


Figure 6.84: Apartment Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

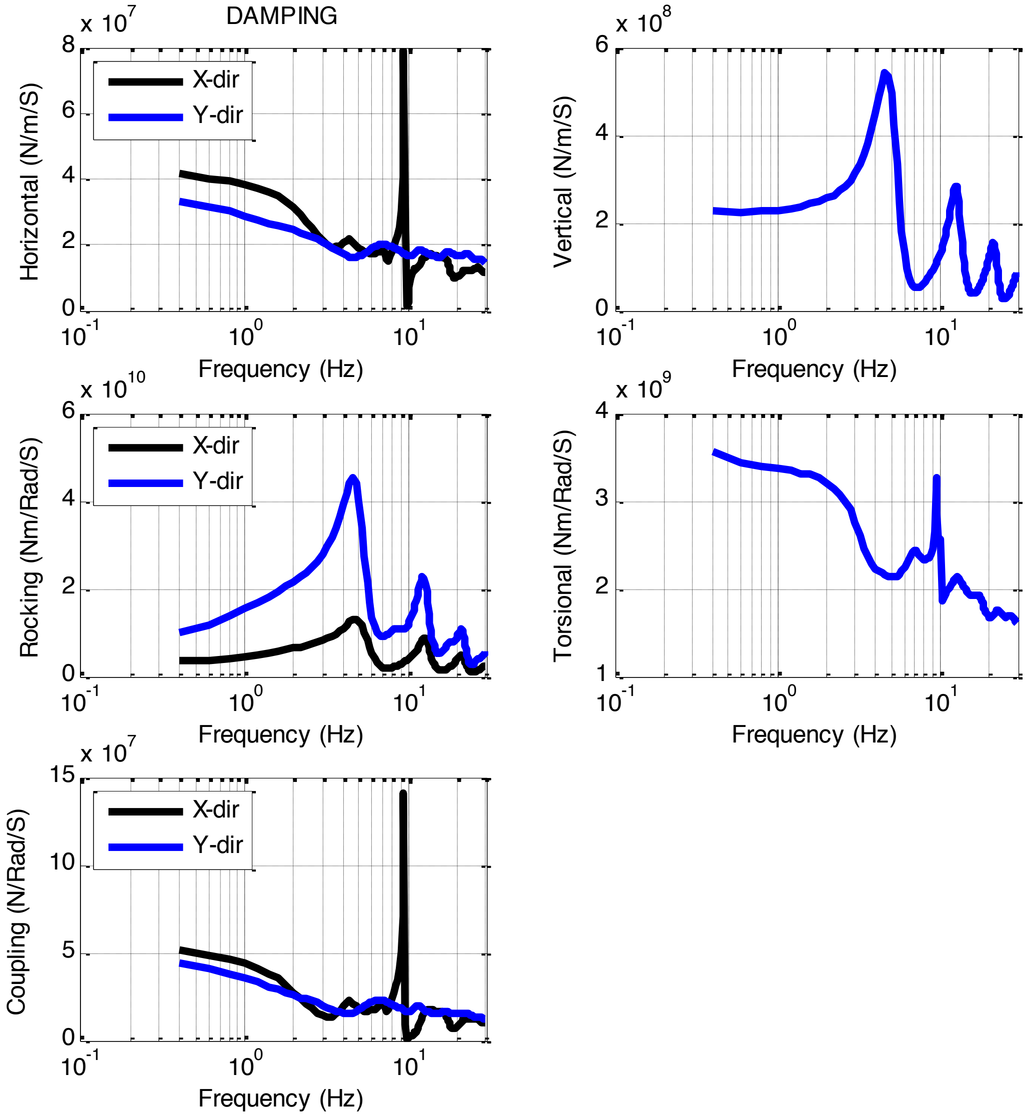


Figure 6.85: Apartment Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

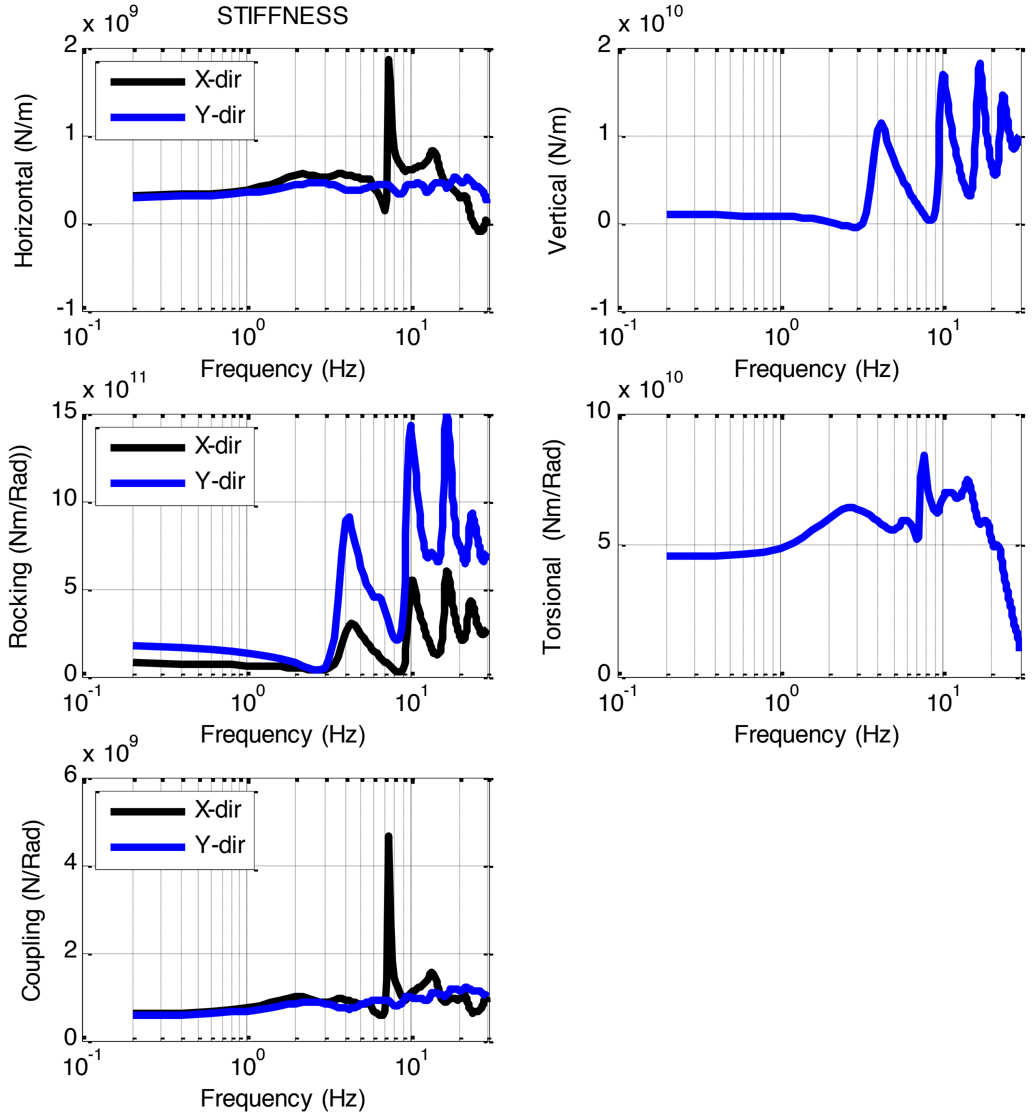


Figure 6.86: Apartment Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

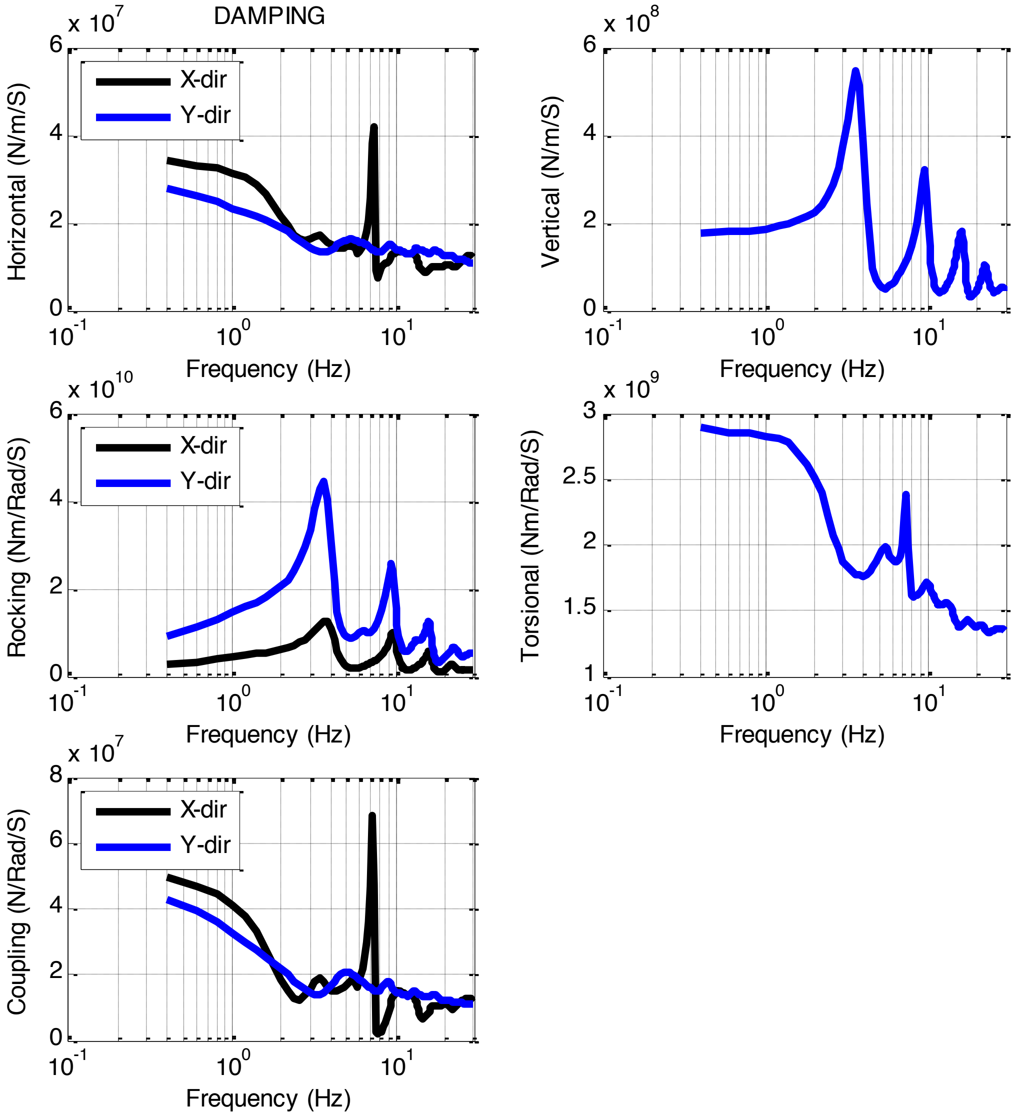


Figure 6.87: Apartment Building on deep foundations – Fixed head conditions – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

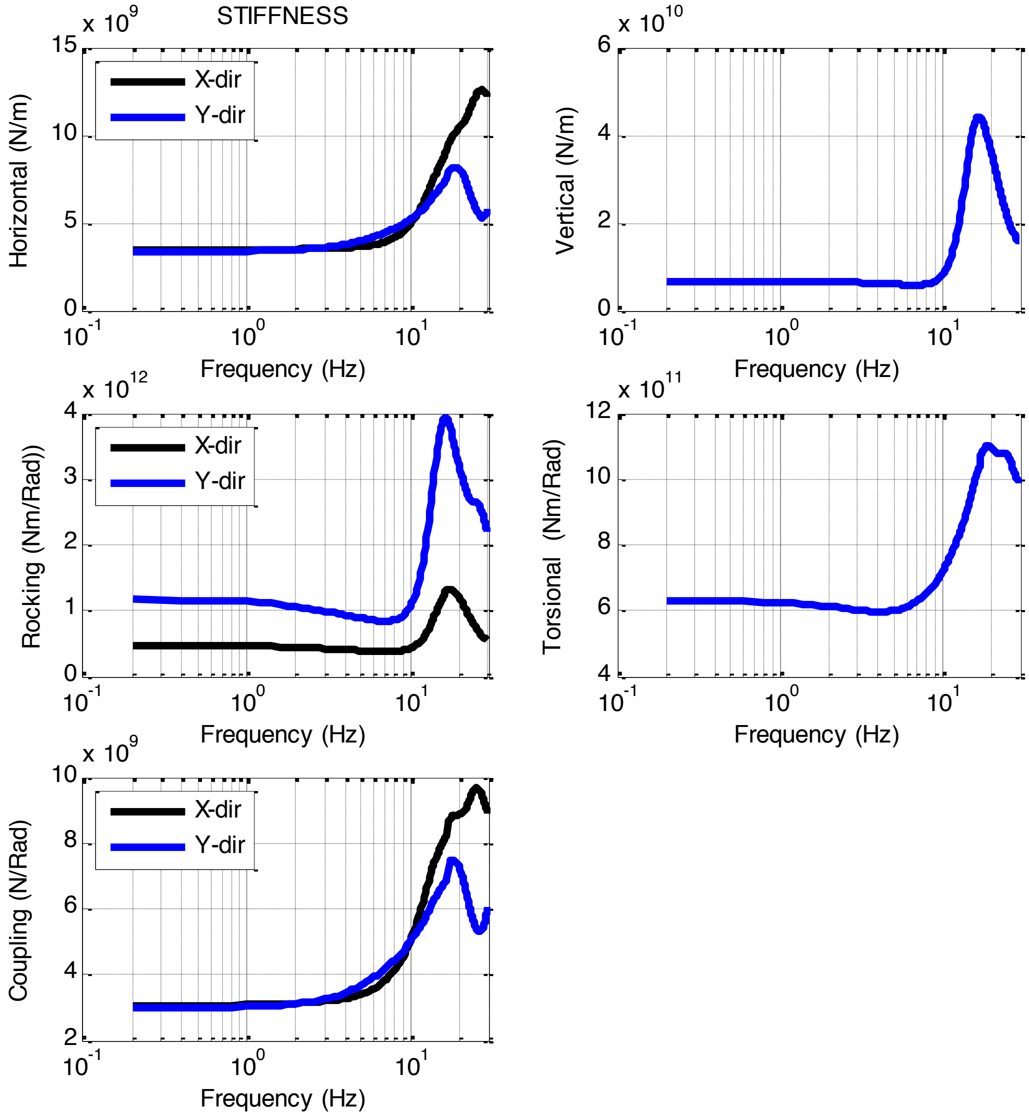


Figure 6.88: Apartment Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

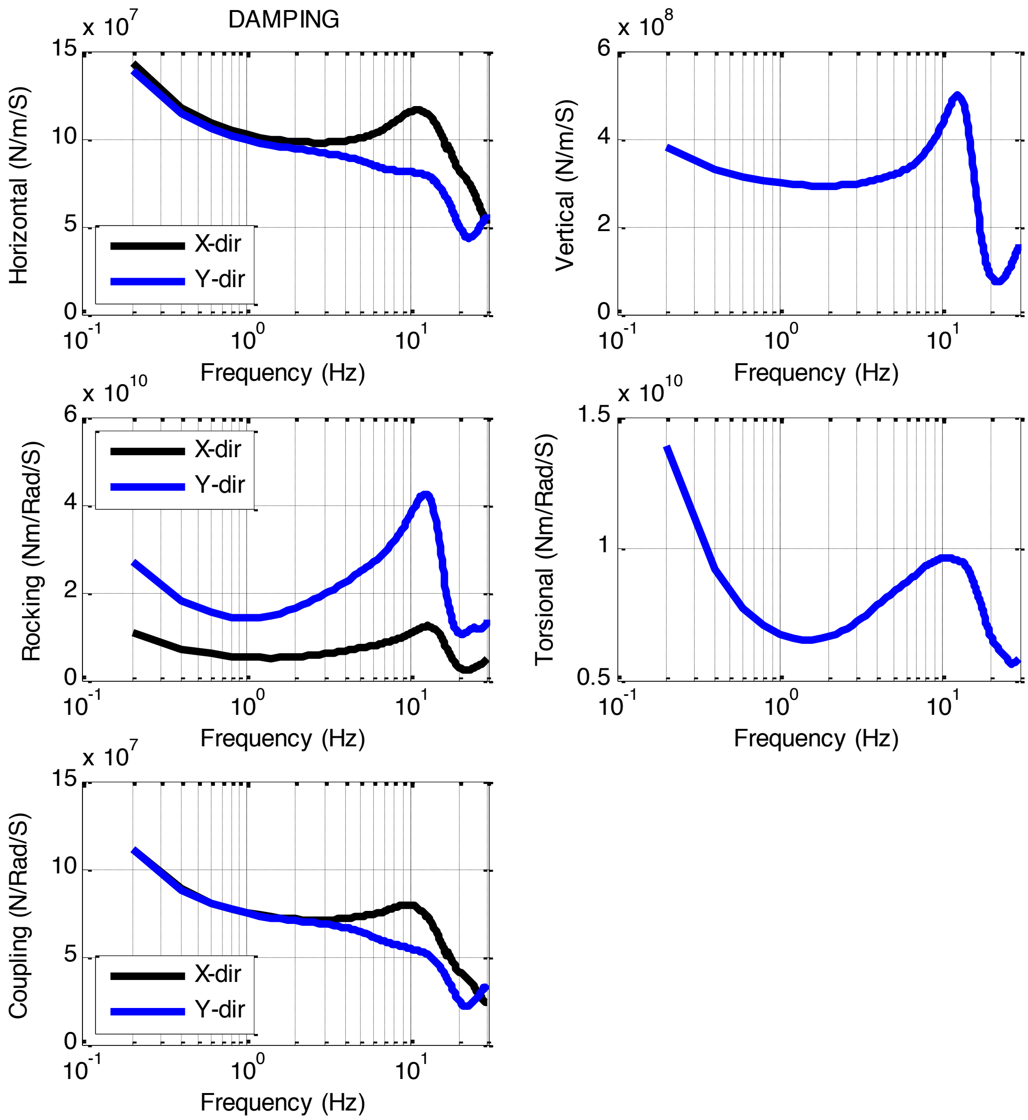


Figure 6.89: Apartment Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

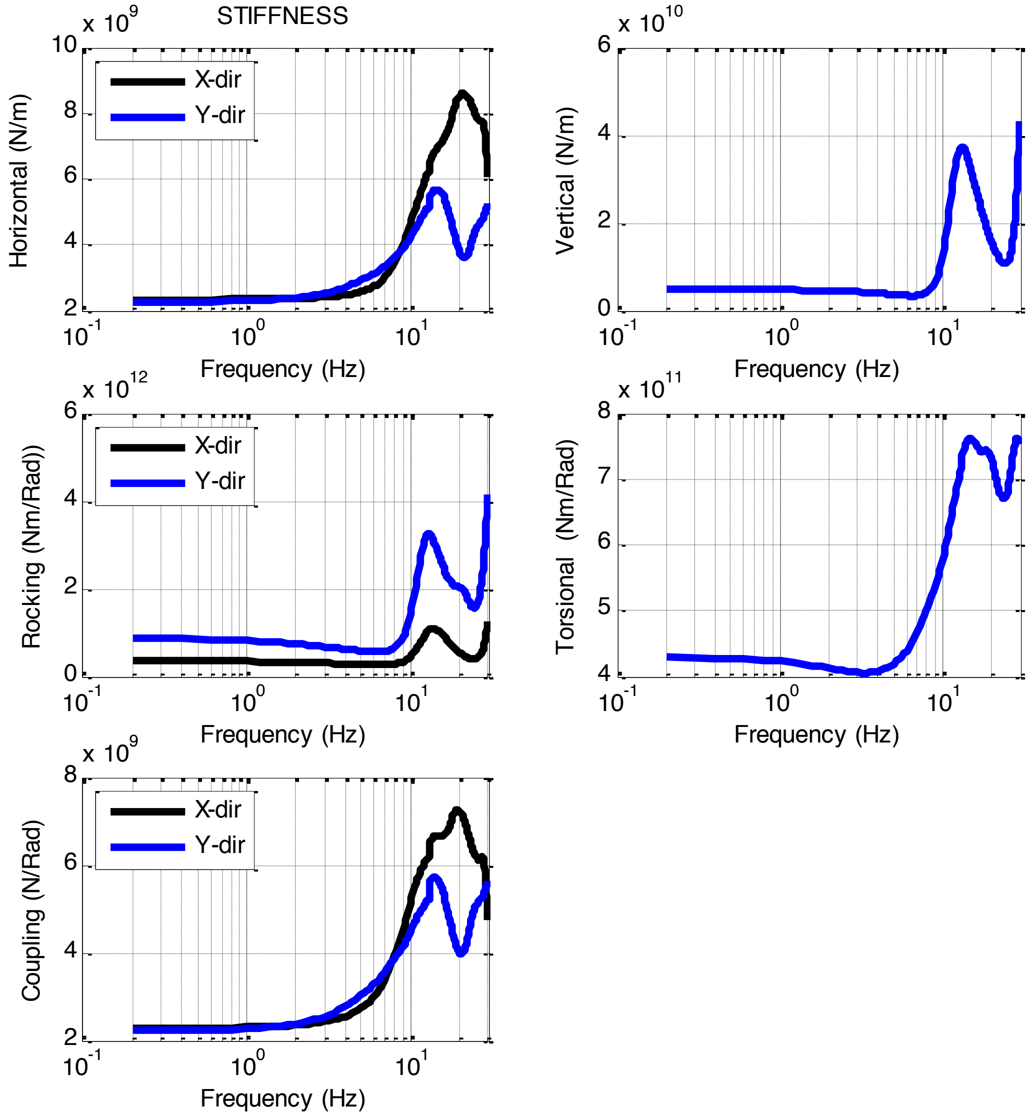


Figure 6.90: Apartment Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

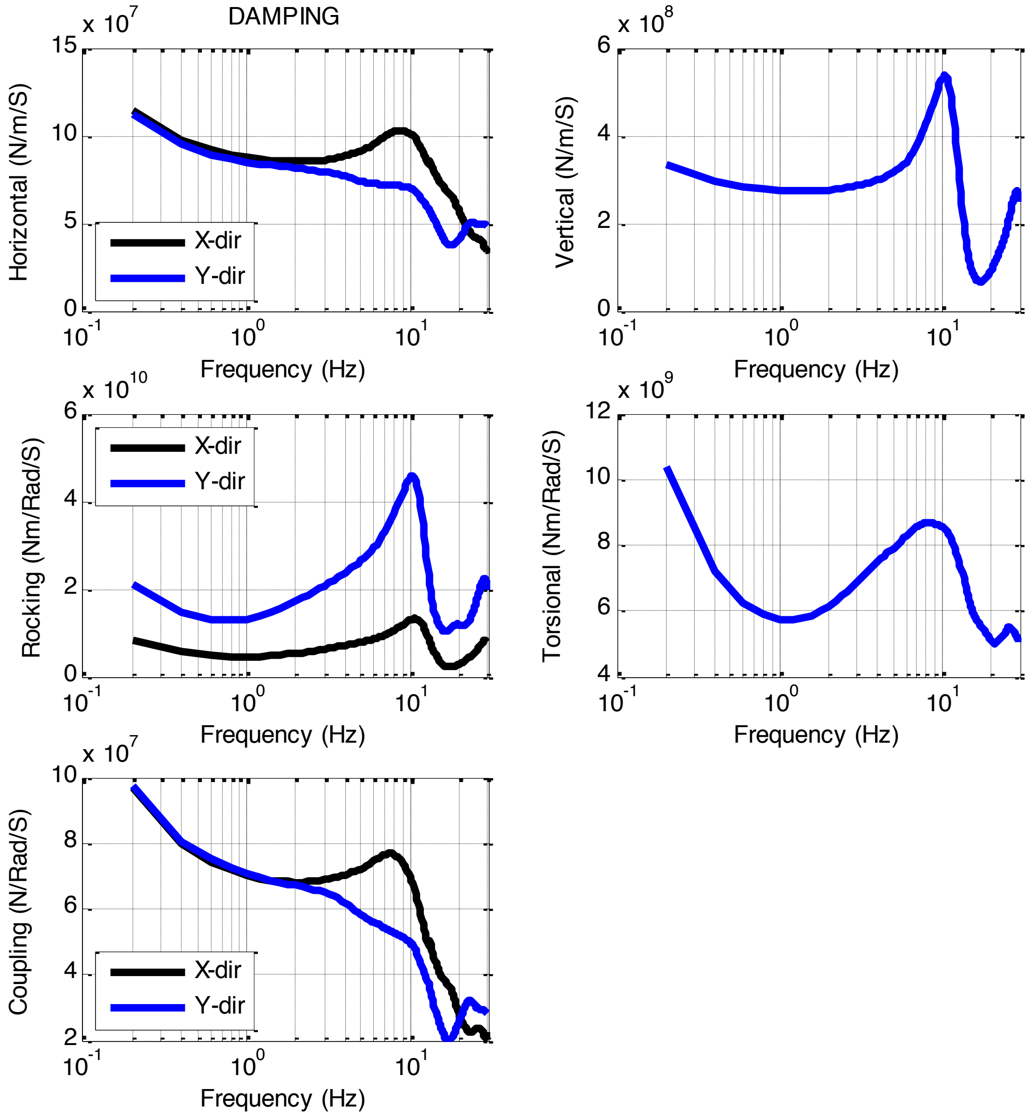


Figure 6.91: Apartment Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

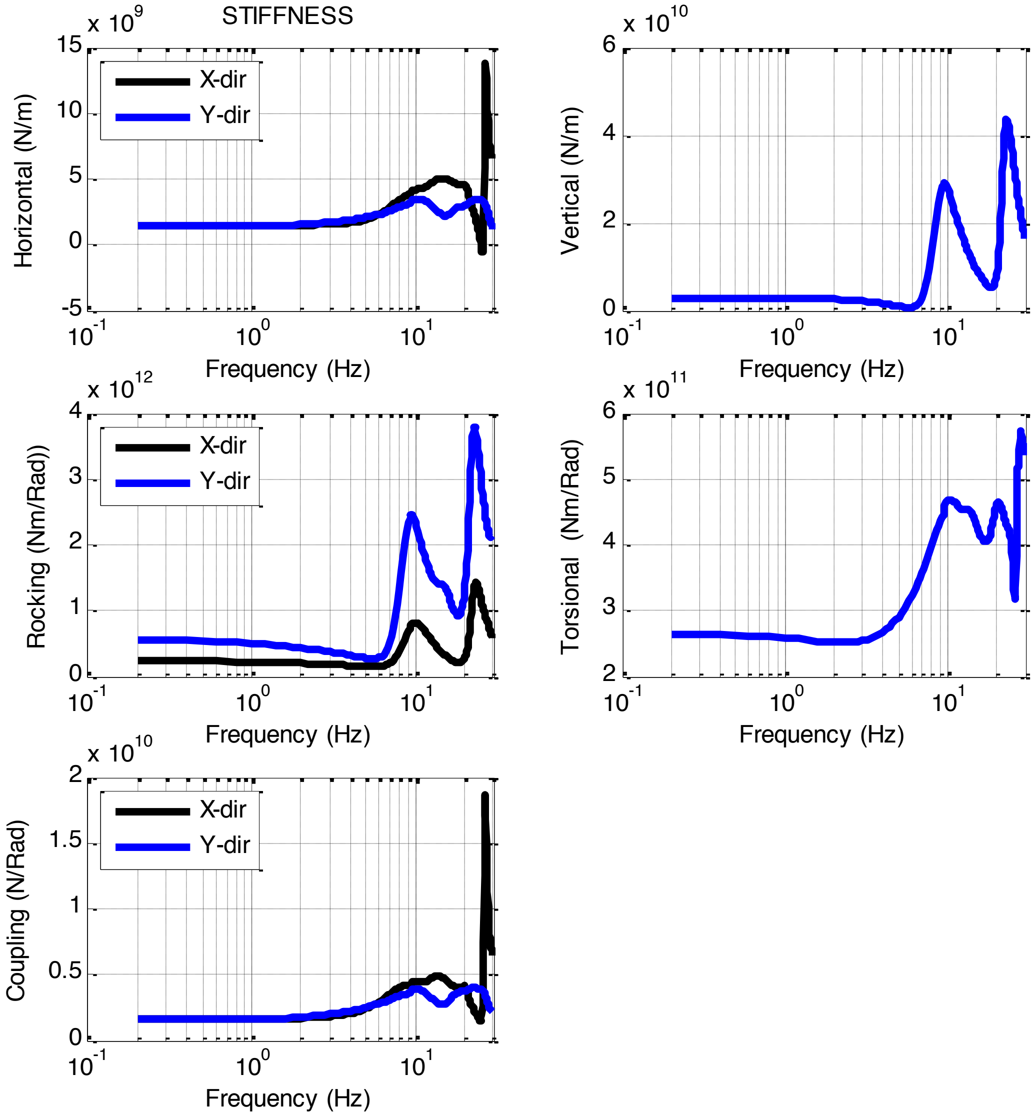


Figure 6.92: Apartment Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

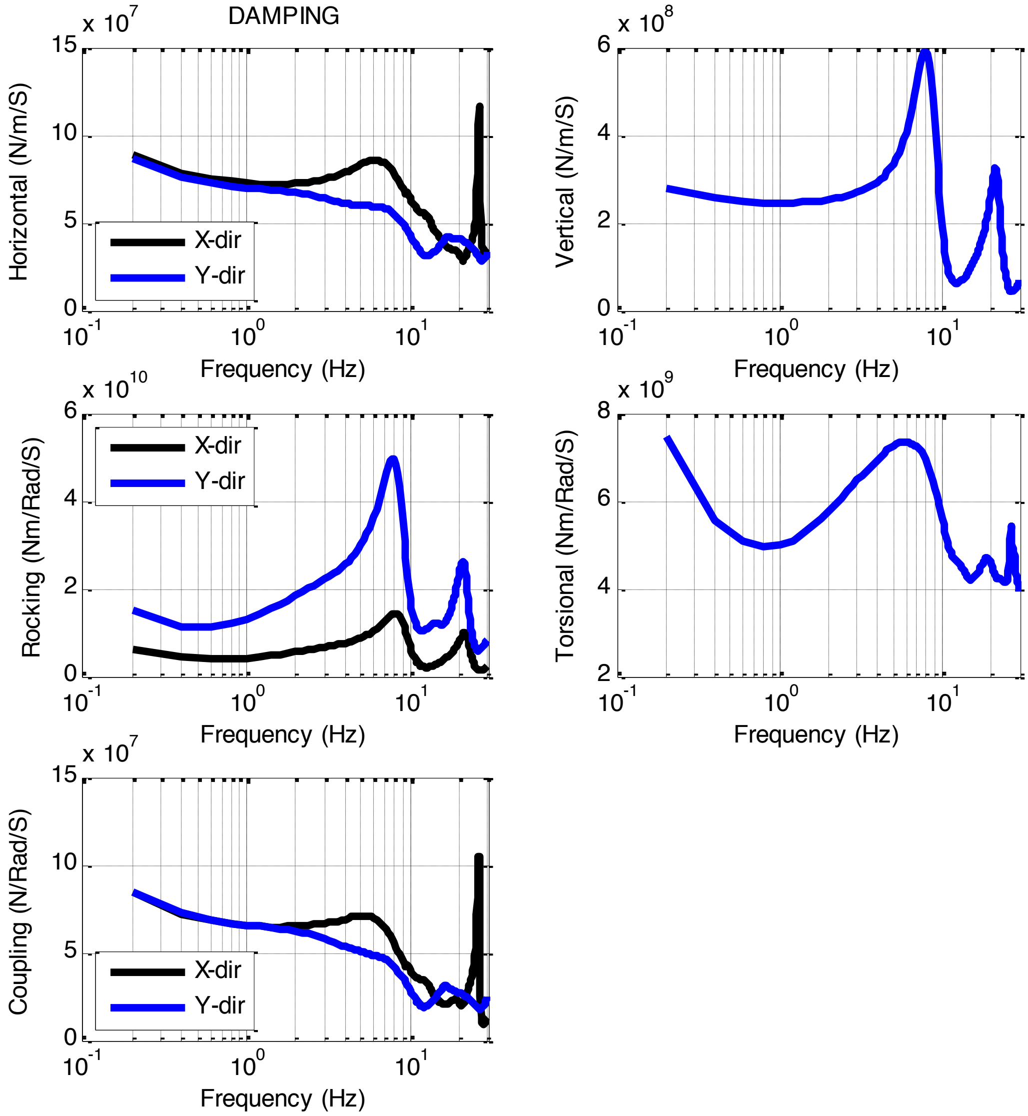


Figure 6.93: Apartment Building on deep foundations – Fixed head conditions – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

6.3.2 Pinned head conditions

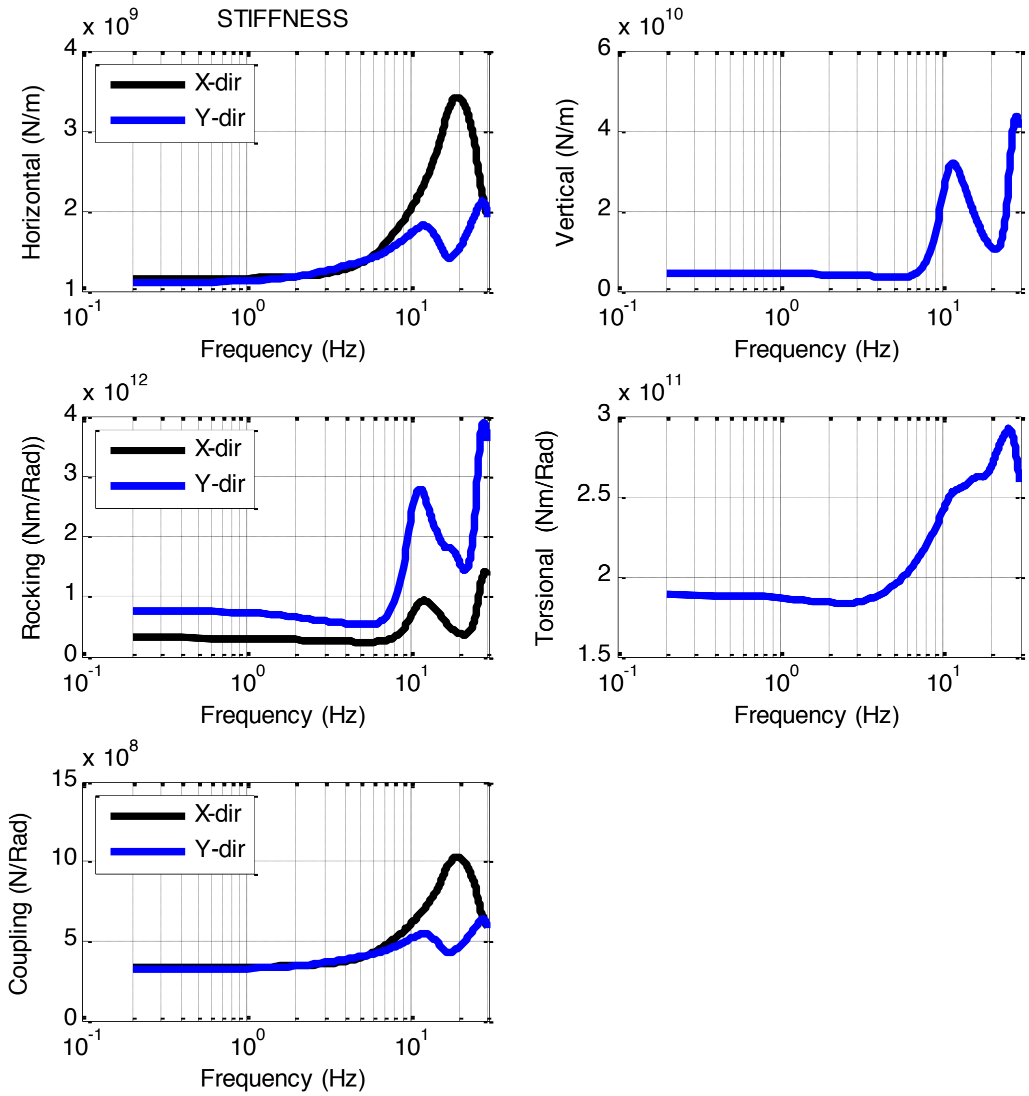


Figure 6.94: Apartment Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF1: STIFFNESS

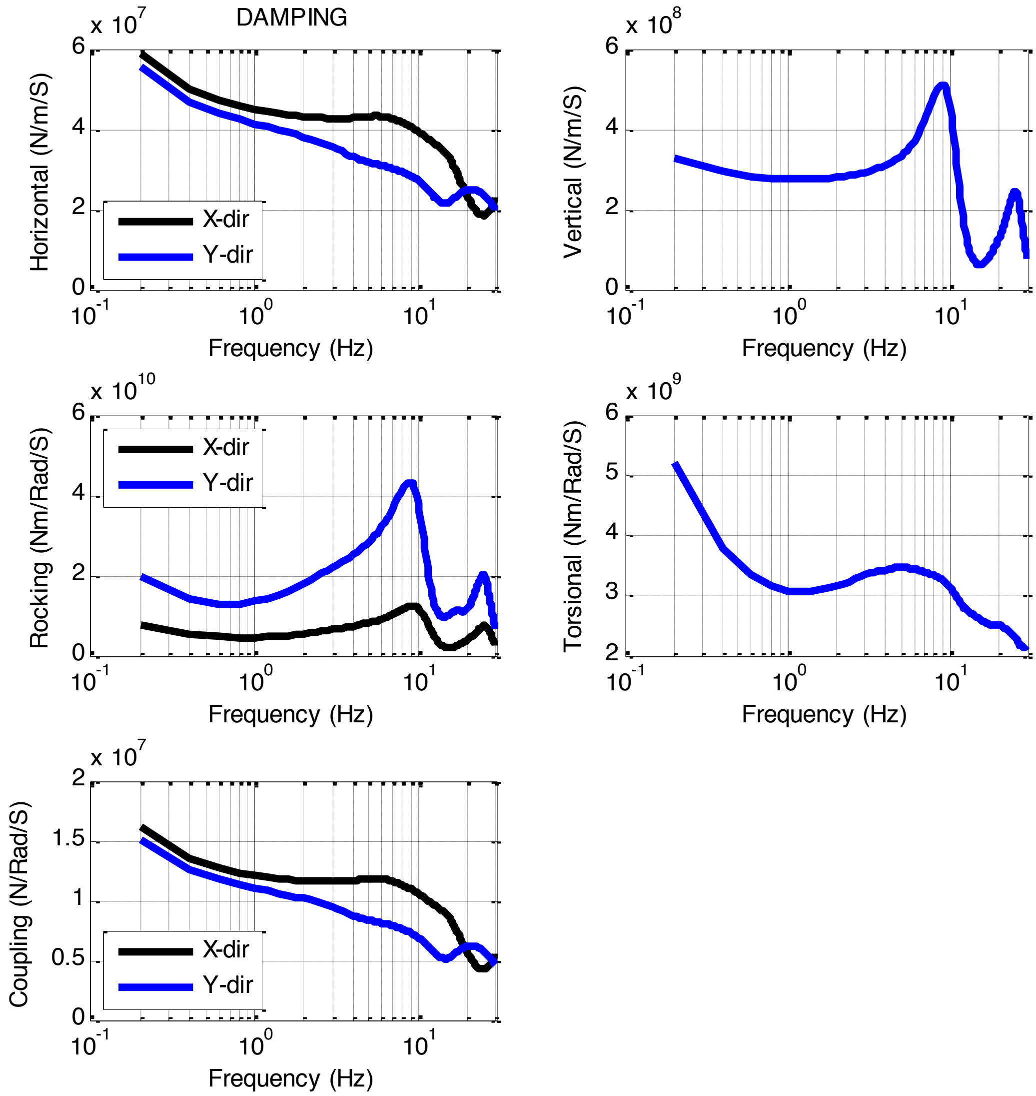


Figure 6.95: Apartment Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF1: DAMPING

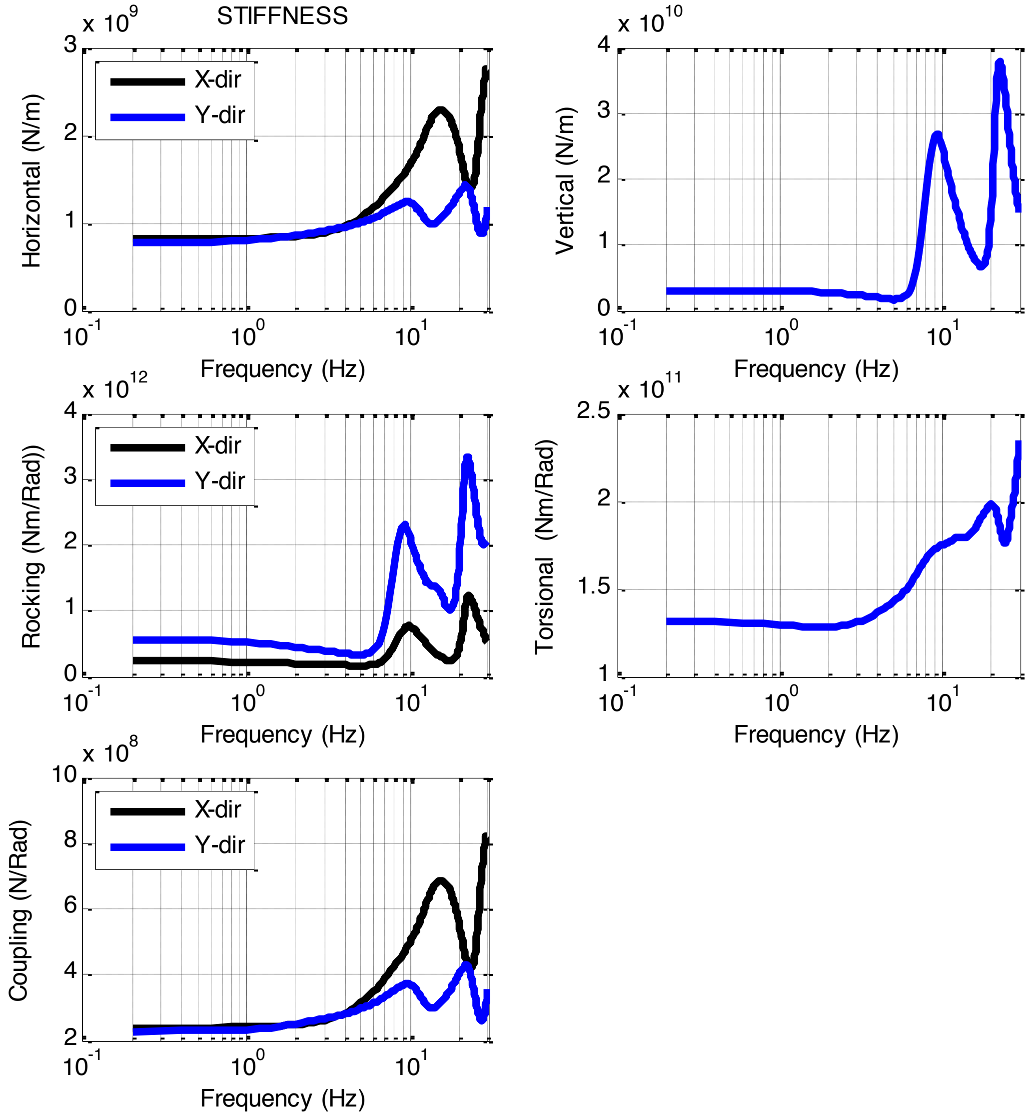


Figure 6.96: Apartment Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF2: STIFFNESS

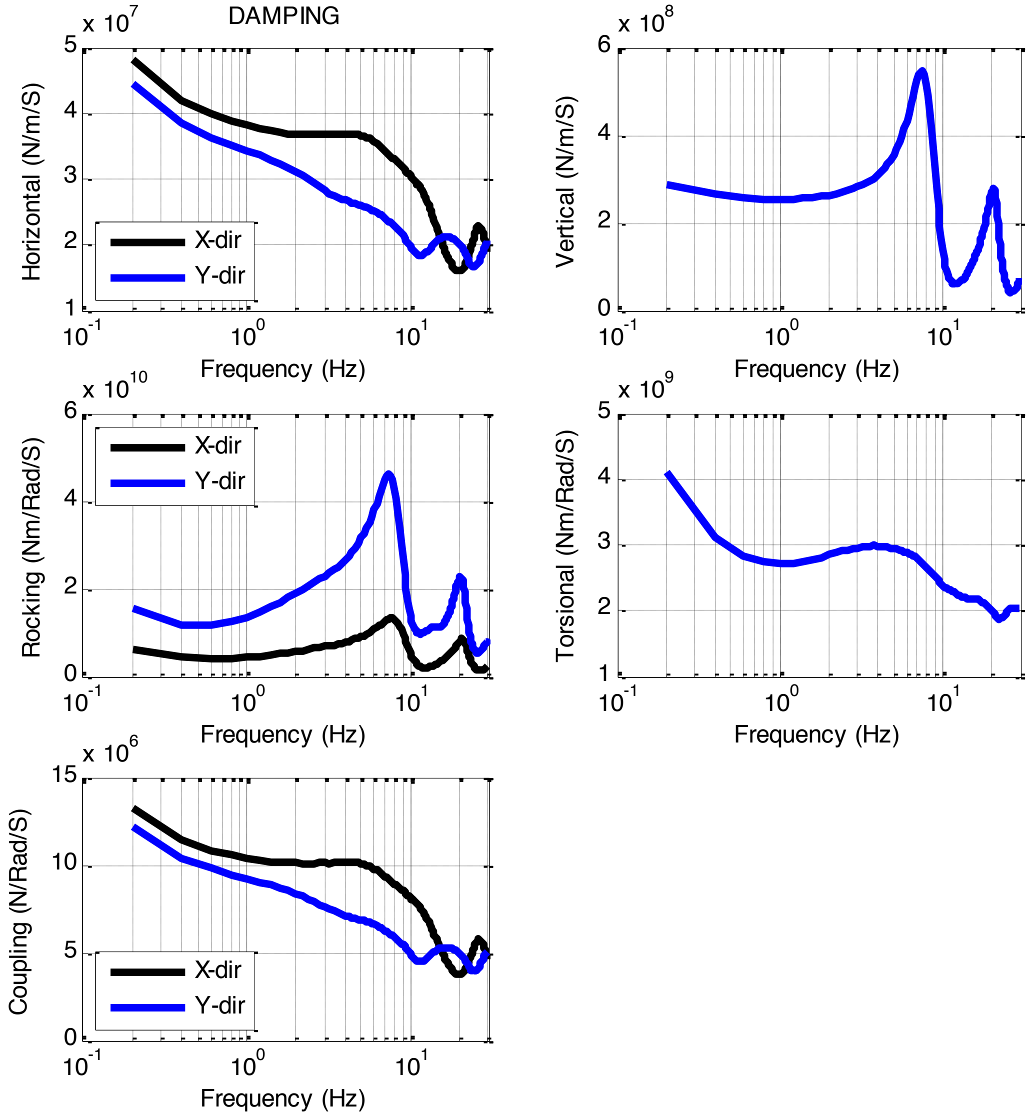


Figure 6.97: Apartment Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF2: DAMPING

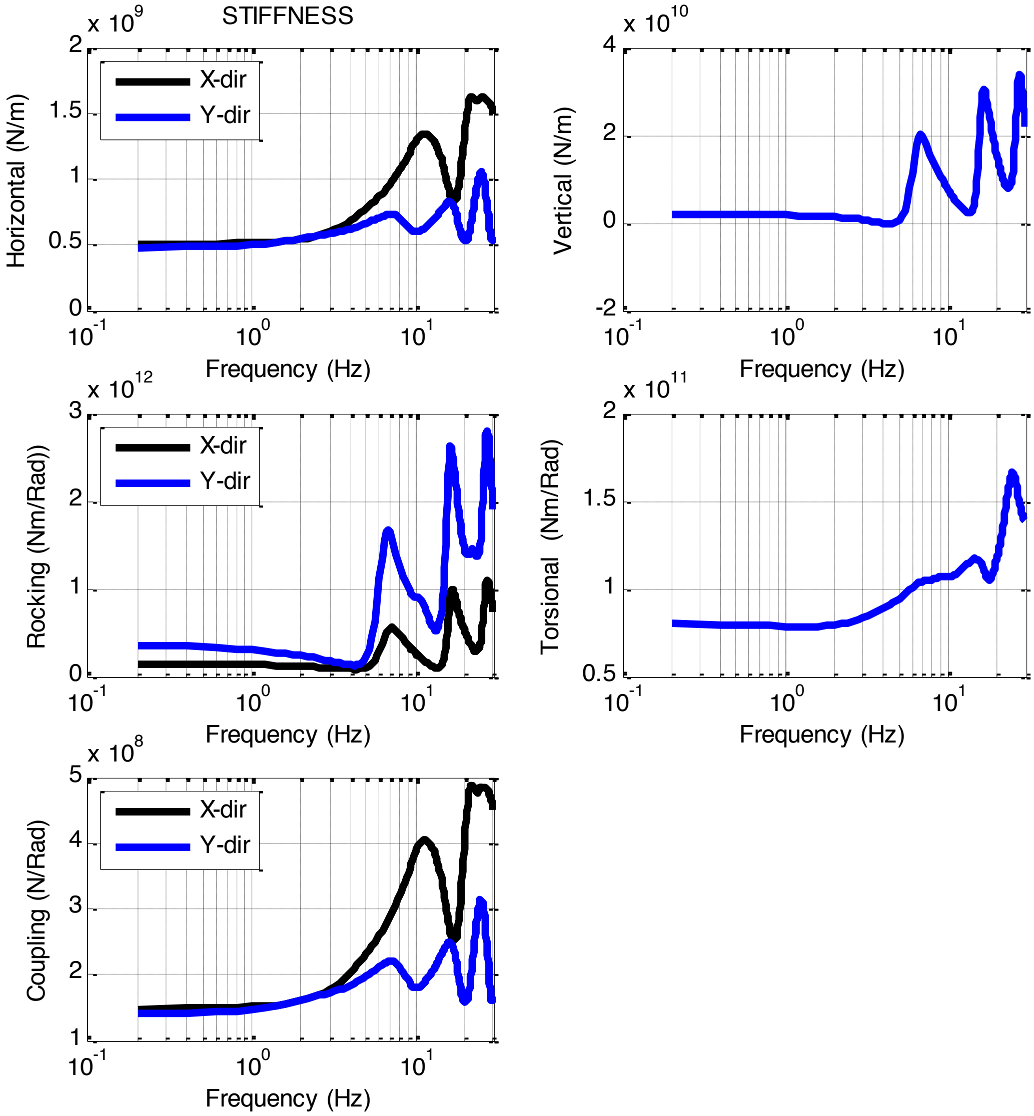


Figure 6.98: Apartment Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF3: STIFFNESS

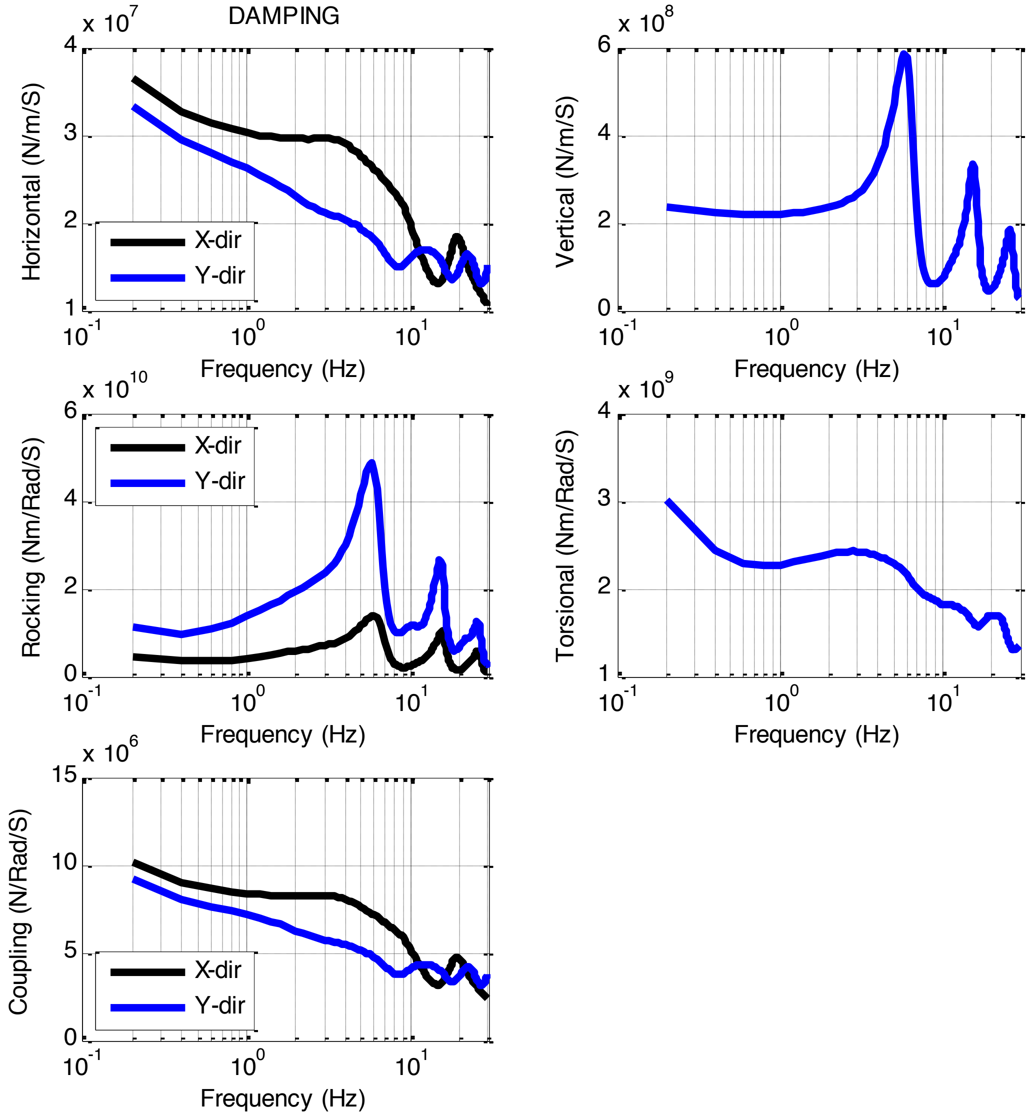


Figure 6.99: Apartment Building on deep foundations – Pinned head conditions – Mean V_S profile with scaling factor SF3: DAMPING

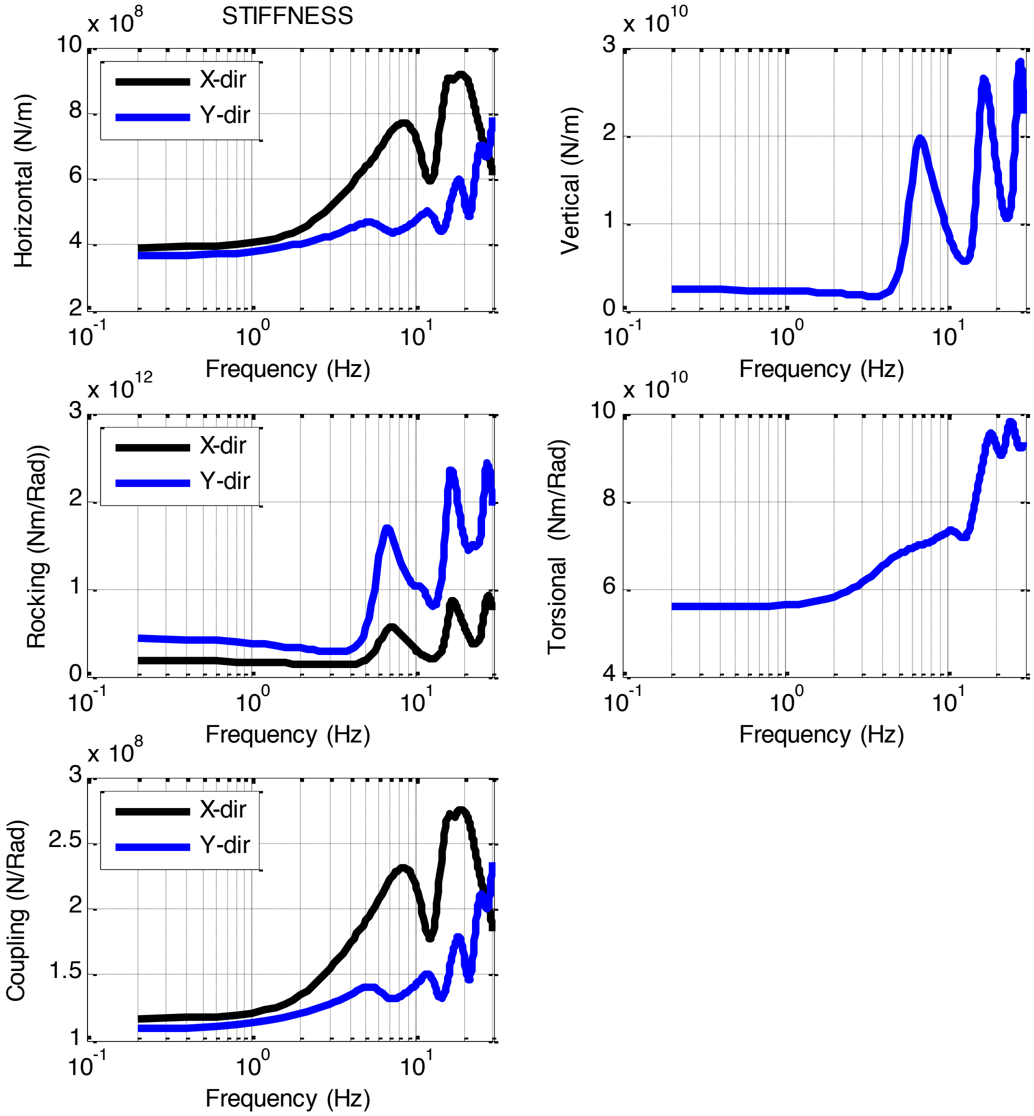


Figure 6.100: Apartment Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF1: STIFFNESS

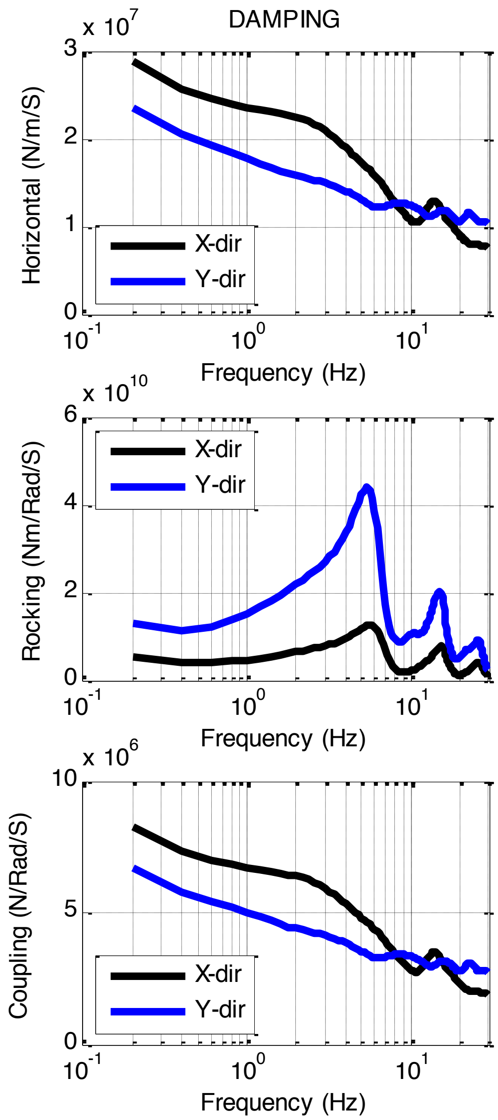


Figure 6.101: Apartment Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF1: DAMPING

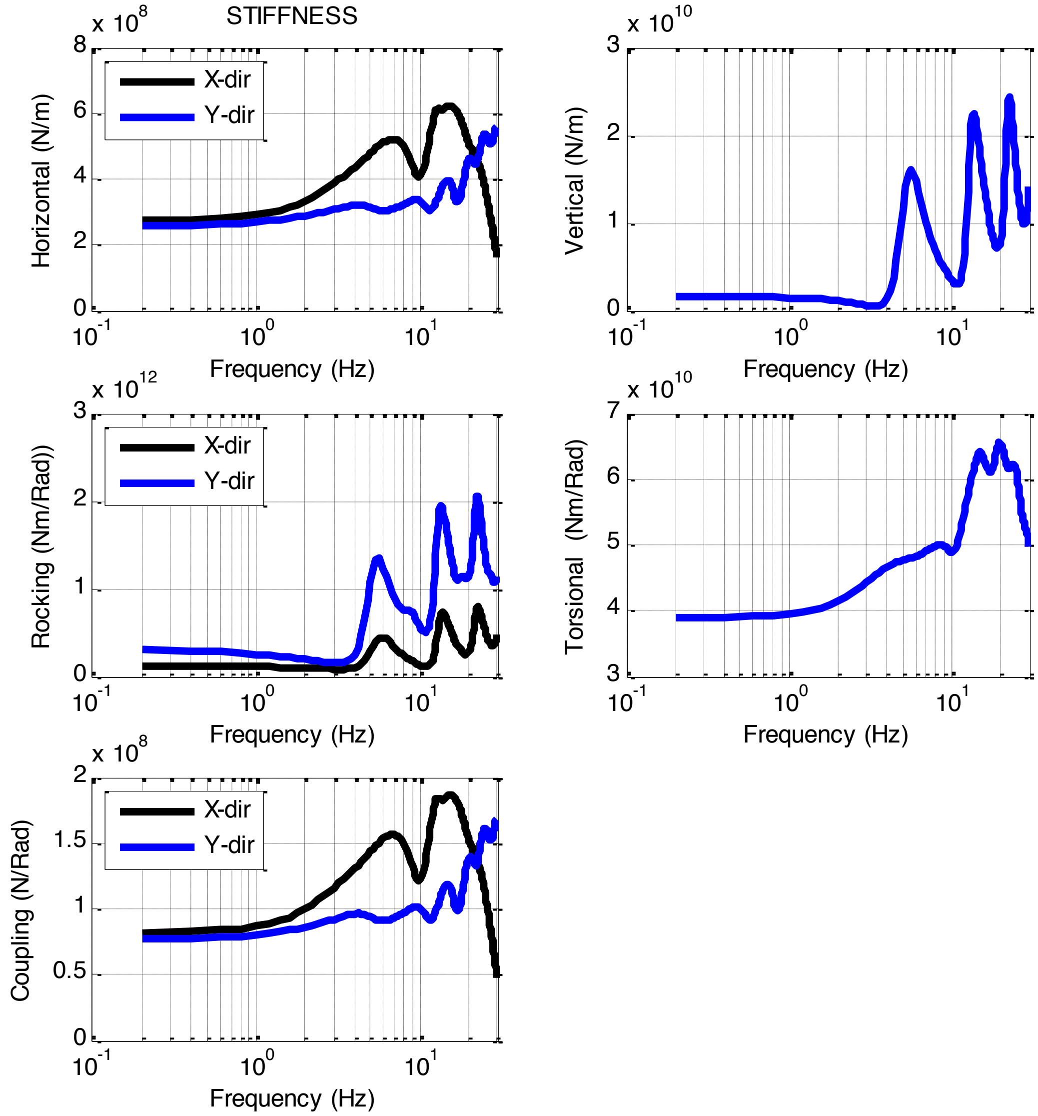


Figure 6.102: Apartment Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF2: STIFFNESS

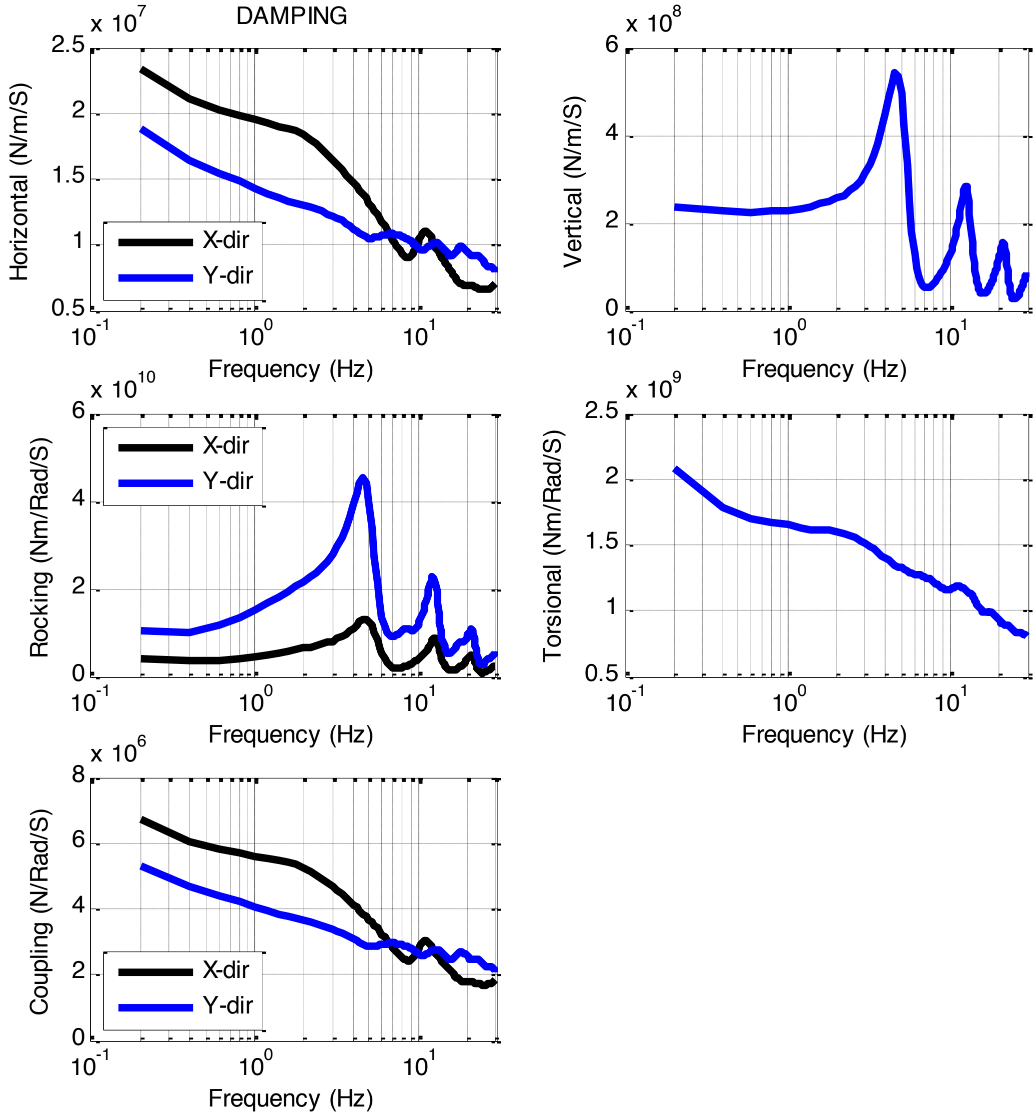


Figure 6.103: Apartment Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF2: DAMPING

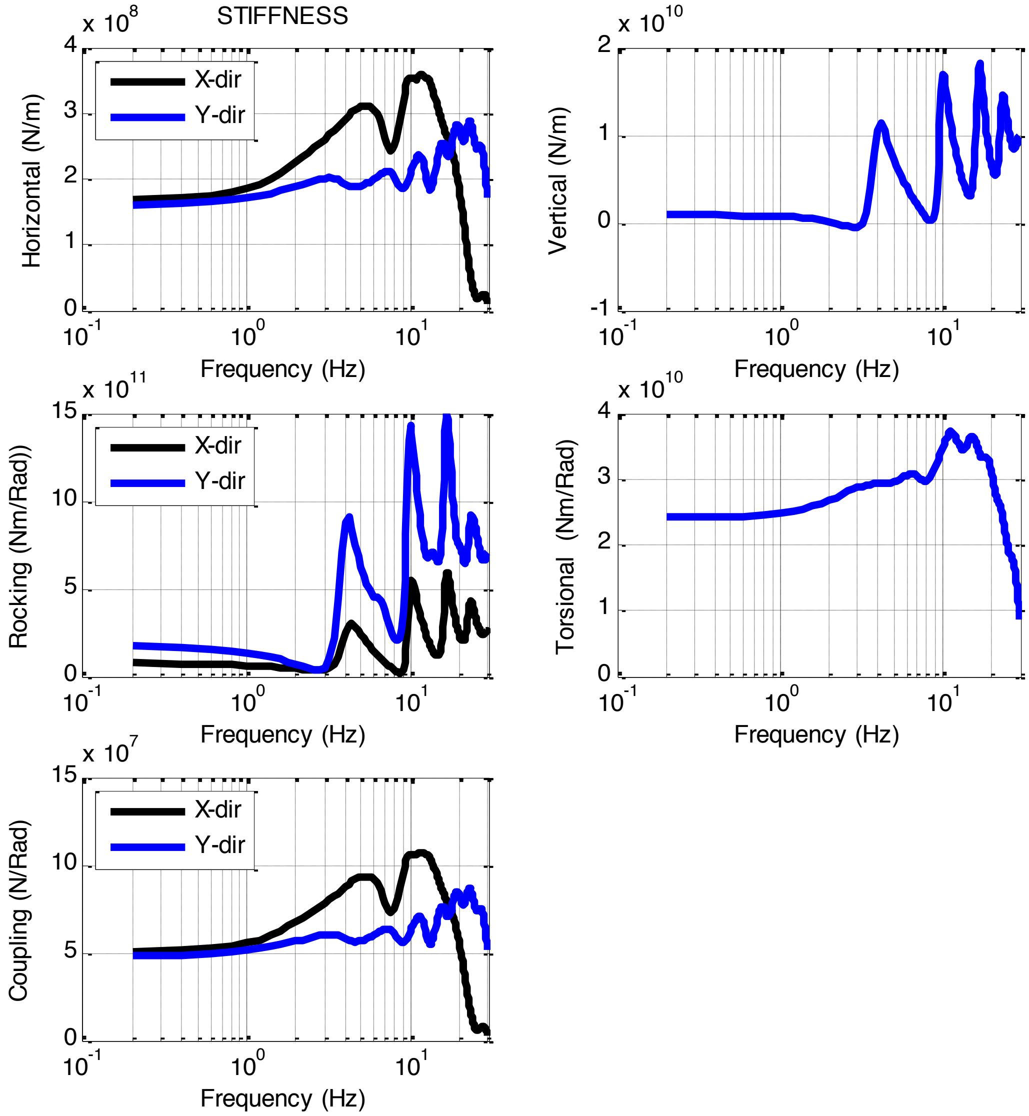


Figure 6.104: Apartment Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF3: STIFFNESS

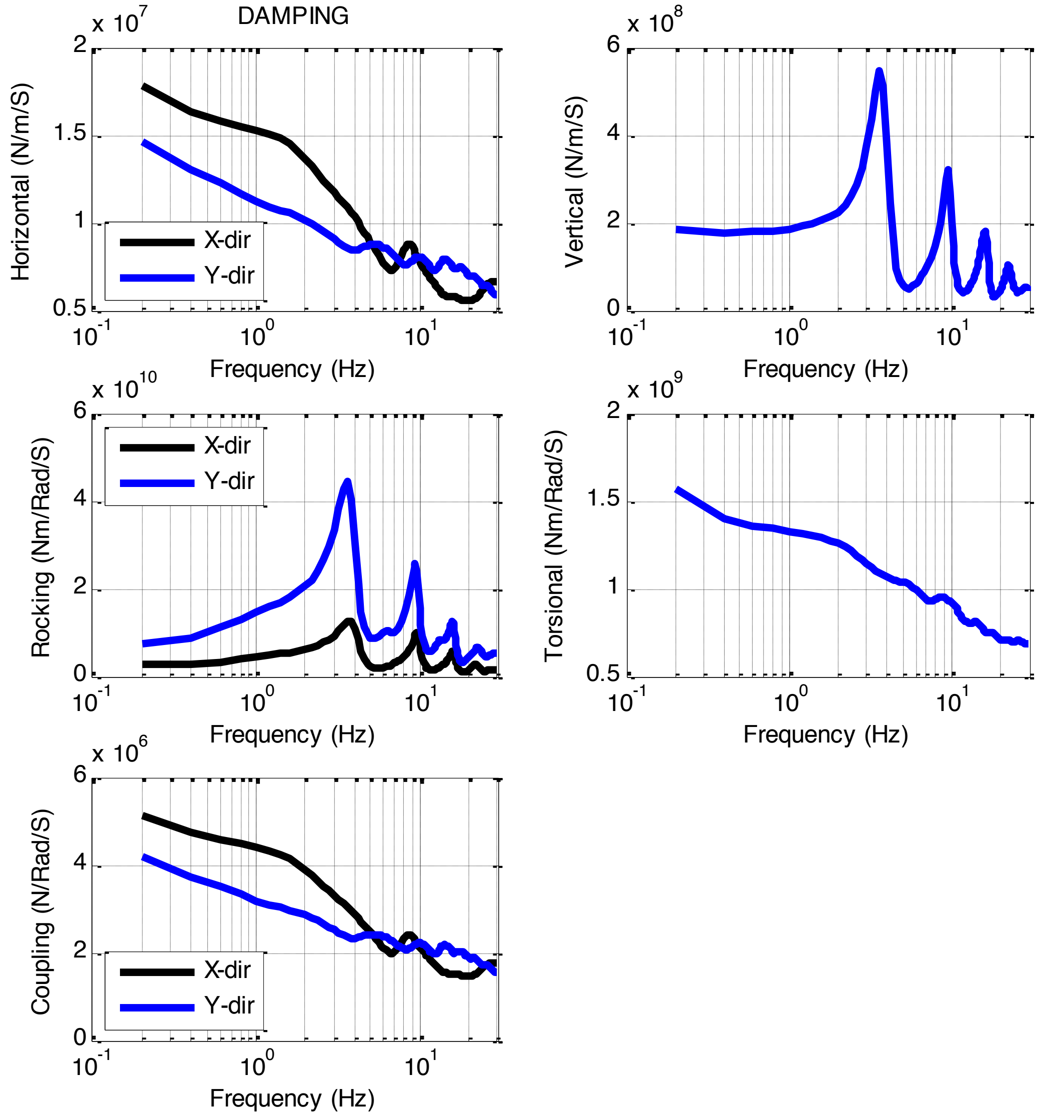


Figure 6.105: Apartment Building on deep foundations – Pinned head conditions – Mean – standard deviation V_S profile with scaling factor SF3: DAMPING

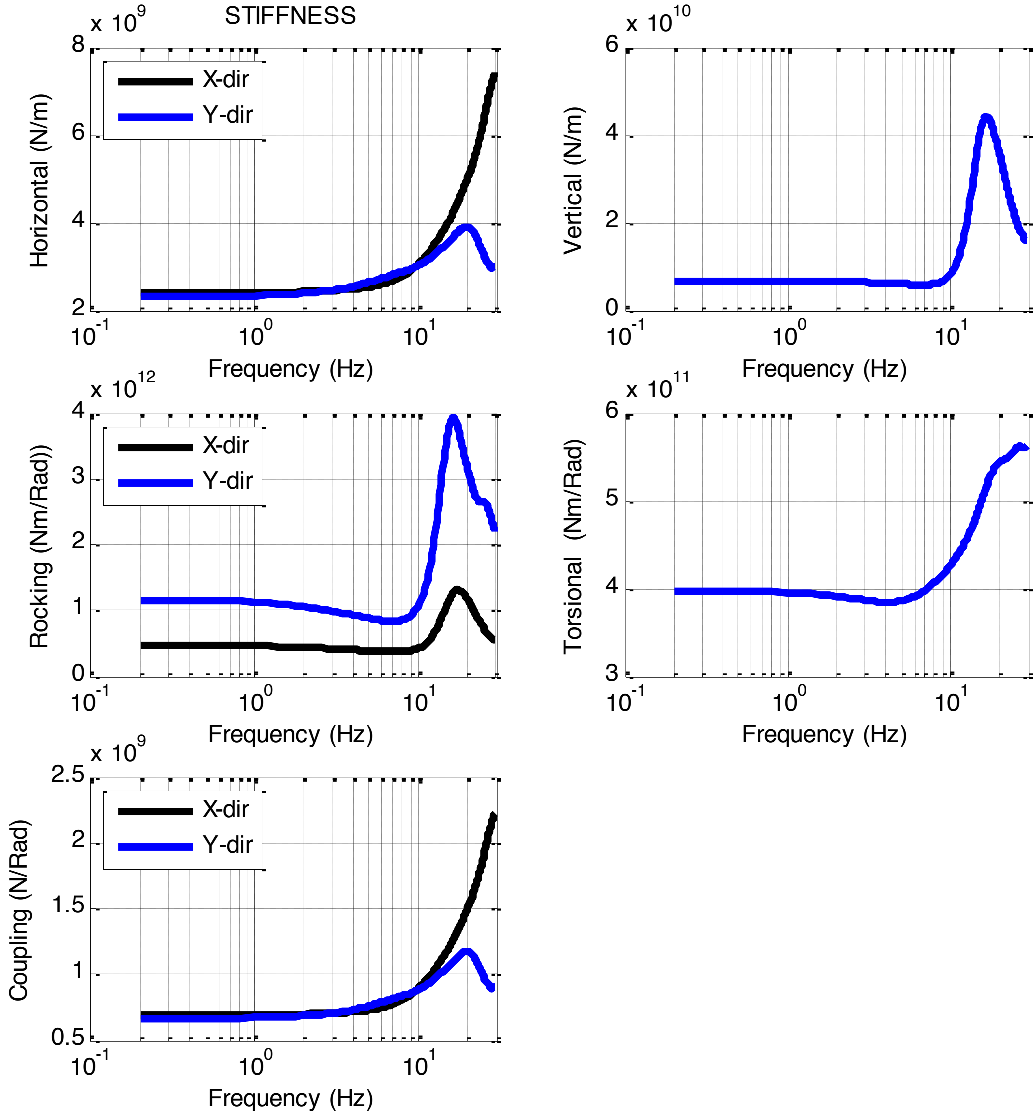


Figure 6.106: Apartment Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF1: STIFFNESS

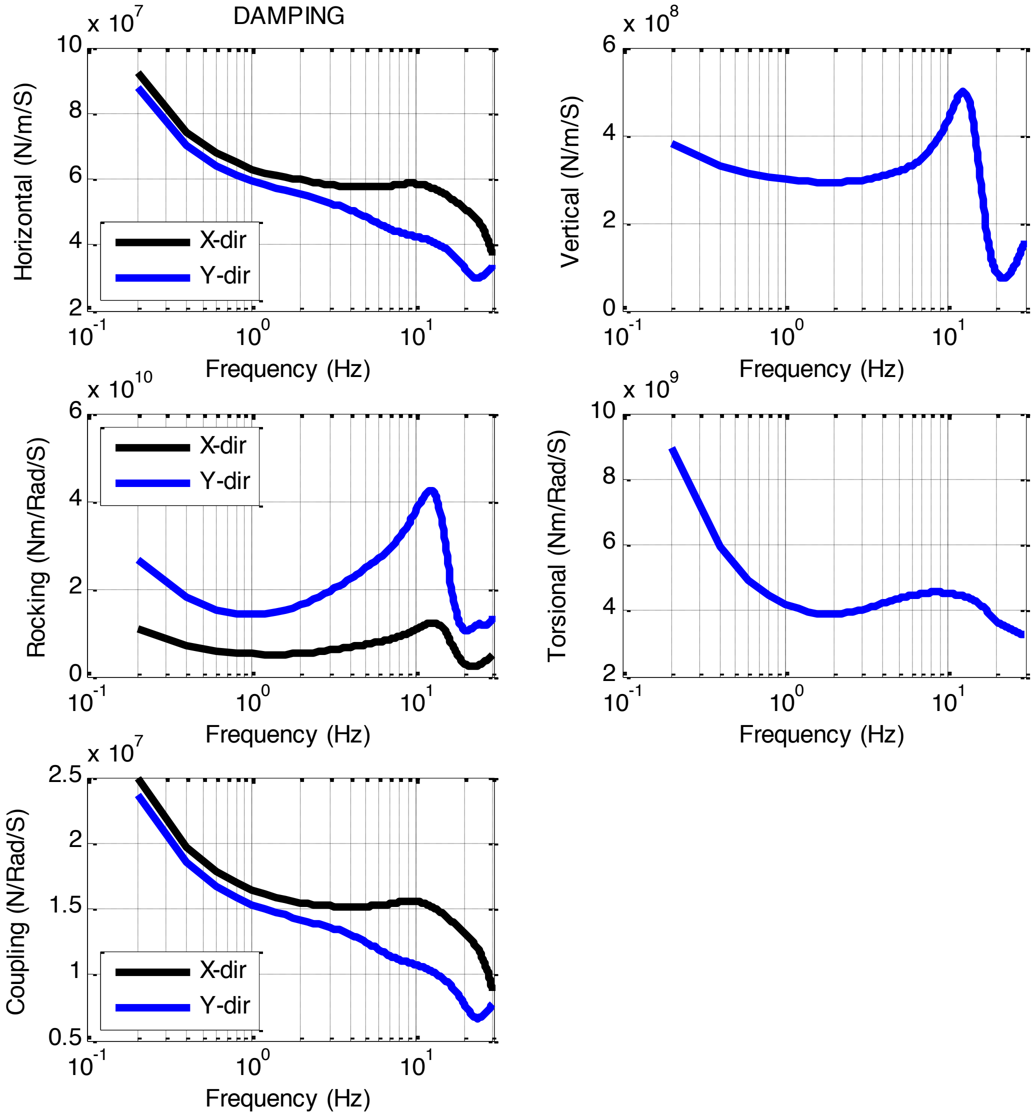


Figure 6.107: Apartment Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF1: DAMPING

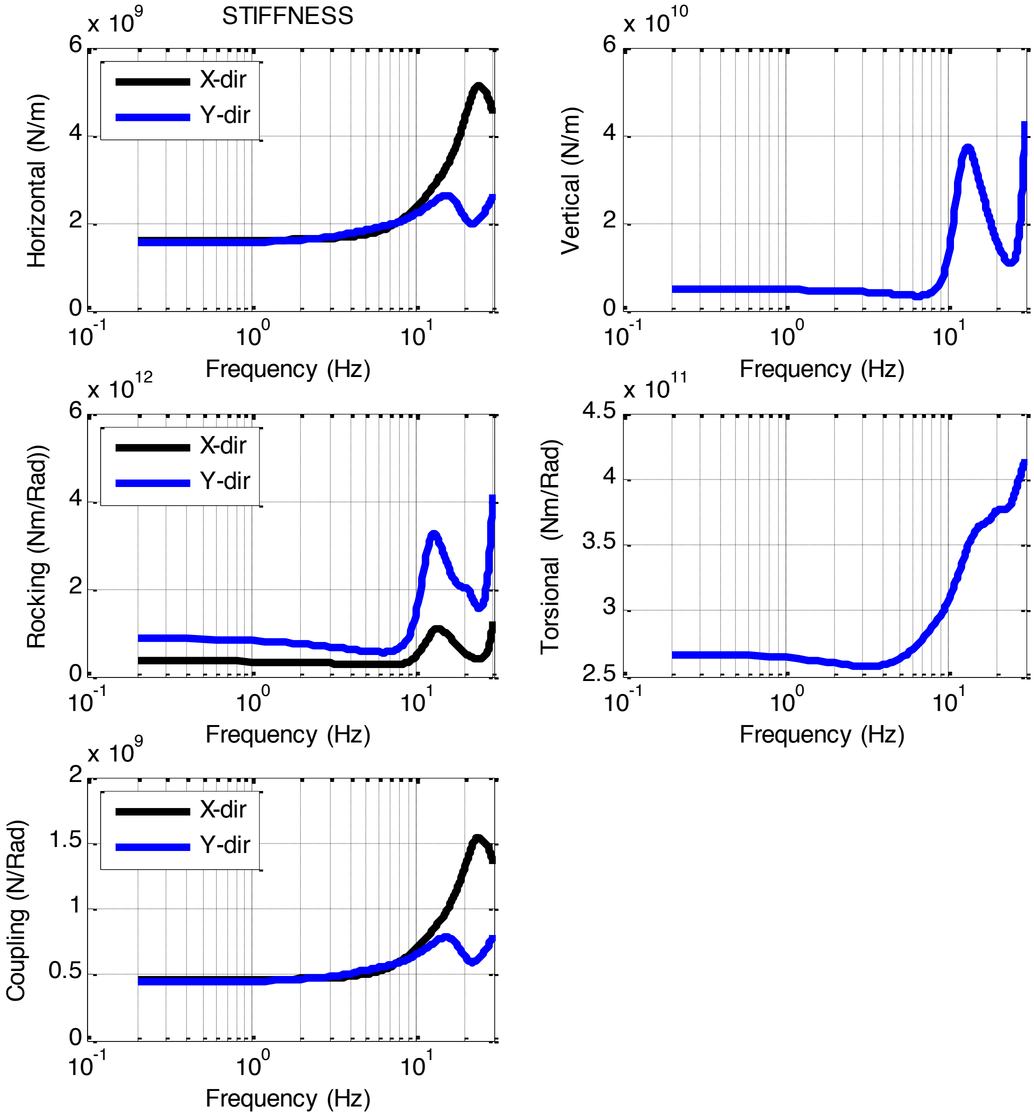


Figure 6.108: Apartment Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF2: STIFFNESS

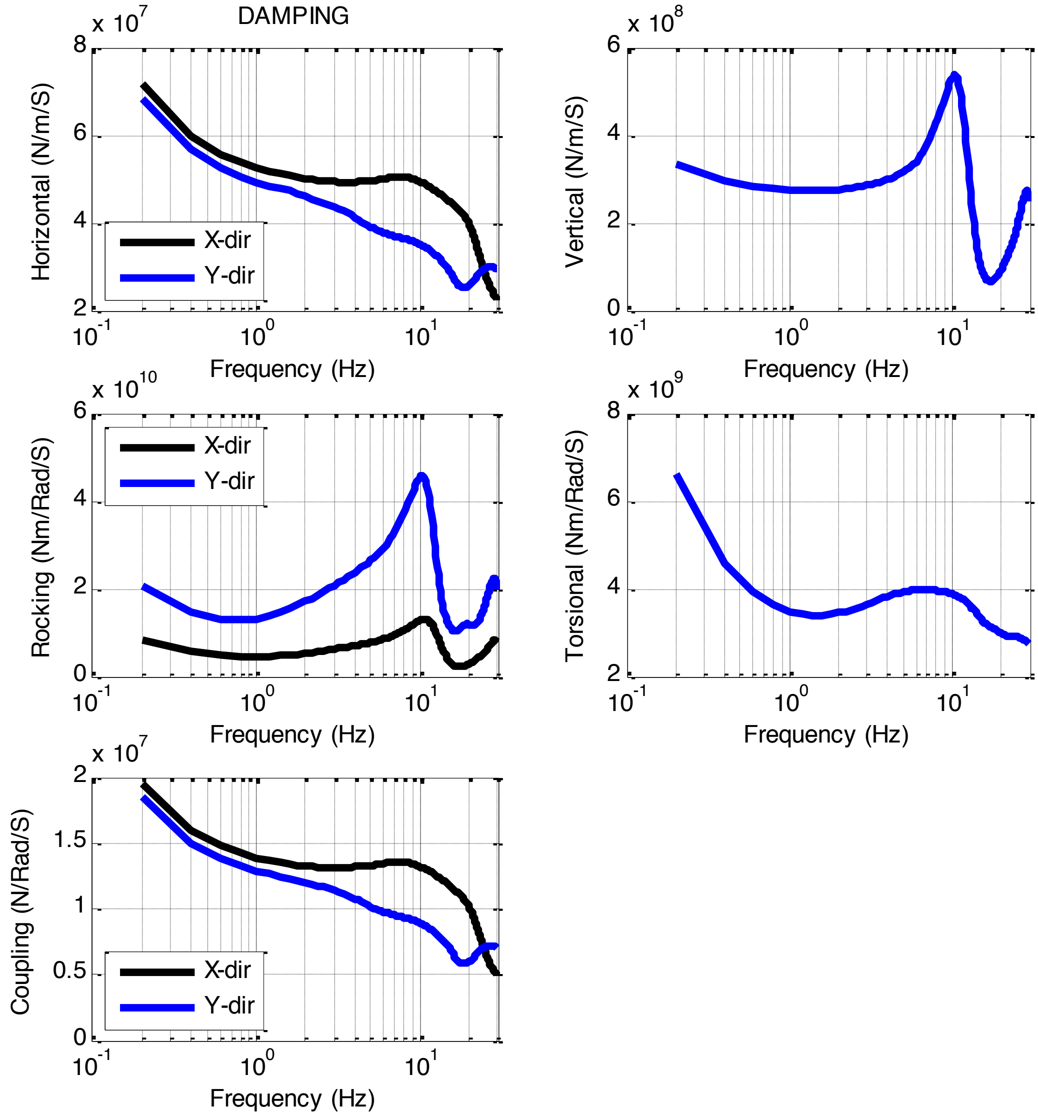


Figure 6.109: Apartment Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF2: DAMPING

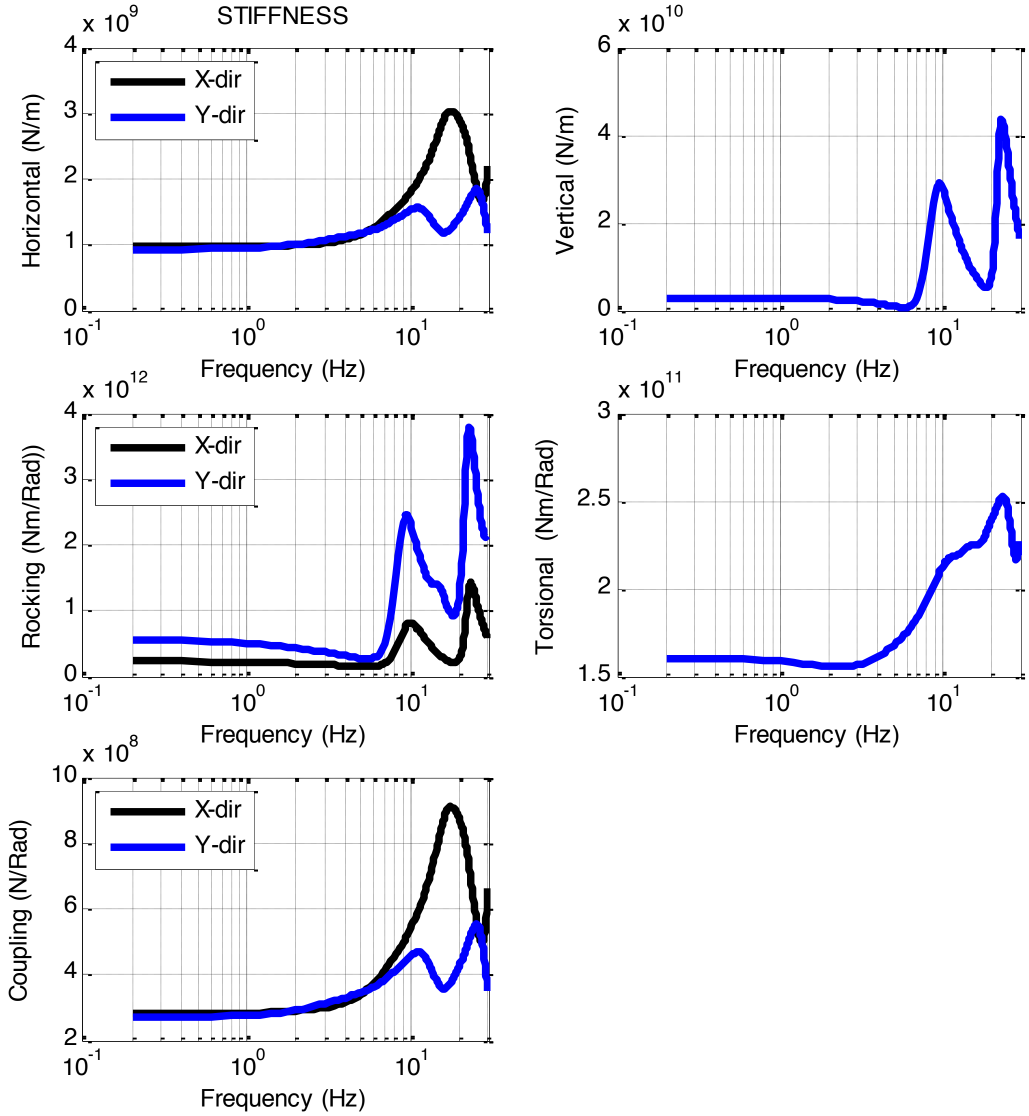


Figure 6.110: Apartment Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF3: STIFFNESS

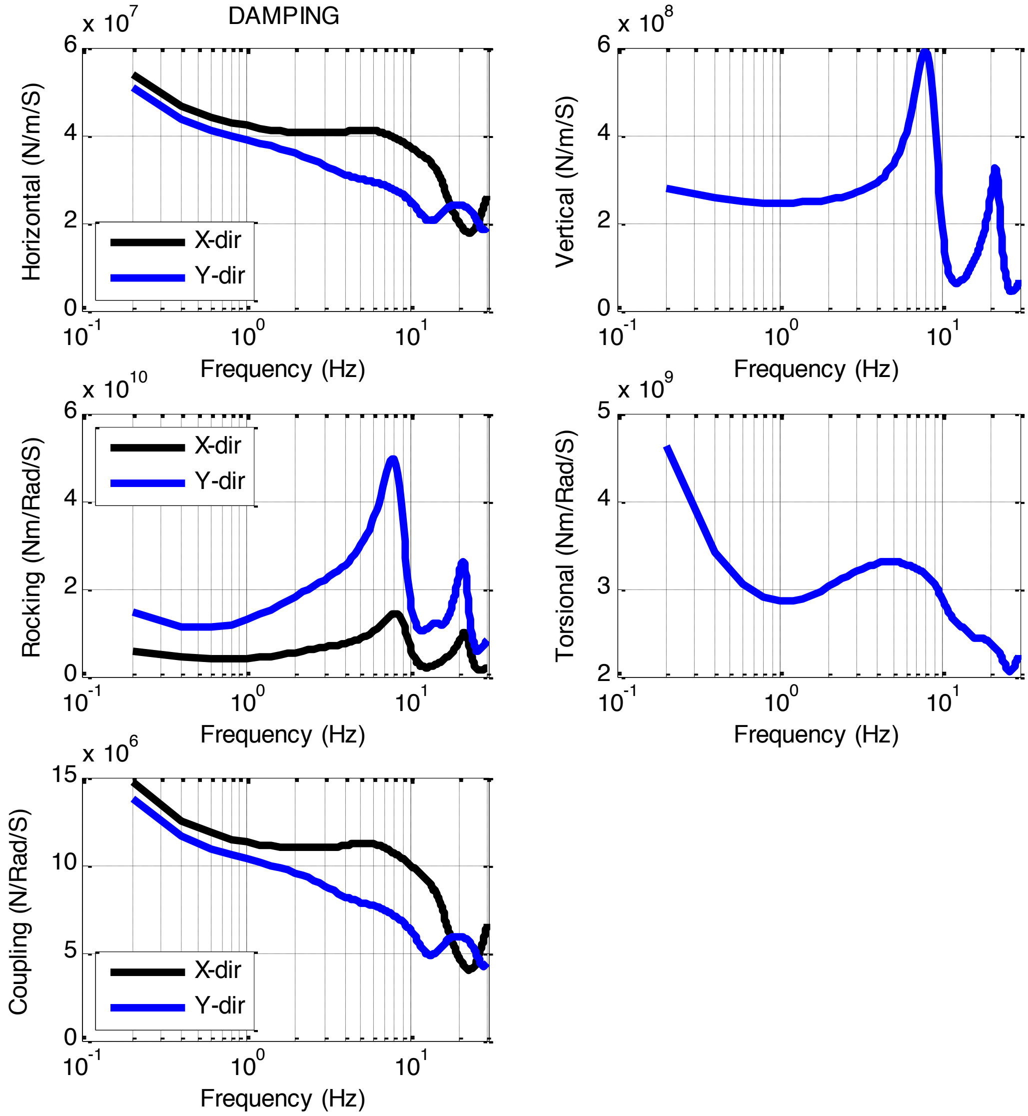


Figure 6.111: Apartment Building on deep foundations – Pinned head conditions – Mean + standard deviation V_S profile with scaling factor SF3: DAMPING

Recommendations for future developments

The report describes the methodology used for the computation of the impedance functions that will be used to account for soil-structure interaction in the numerical simulations for definition of fragility curves in the Groningen area.

In selecting a model, it is necessary to accounting for the "scale" of the problem at hand; the "scale" for definition of fragility curve is inevitably large, because it involves a wide area characterized by different soil properties, different building typologies and foundations types, etc. The larger is the "scale" of the problem, the simpler should be the model from a computational point of view, calibration of the model parameters and processing of the results.

SSI can be taken into account using different approaches, with increasing level of complexity. The first, simpler option consists of the substructure approach, involving the use of linear elastic impedance functions, and it is covered in this report. This method has been widely used in the past and was felt to constitute a sound method of analysis. Despite the general complexity of the SSI, it remains rather simple, thus adequate and very useful for the large "scale" problem being addressed here, as noted above. On the other hand, it does feature some limitations, related, for instance, to the linear elastic constitutive model used, which is not always able to capture some aspects of the soil response, the frequency dependence of the stiffness and damping parameters, which poses a problem in selecting the frequency in time domain analysis, etc.

A step forward in modeling SSI could consist in the adoption of a macro-element approach, a relatively new methodology developed in the last two decades mostly for shallow foundations (e.g. Cremer *et al.*, 2002; Chatzigogos *et al.*, 2011), but also for deep foundations (Correia *et al.*, 2013). It can be included in the sub-structure approach category, because it does not require a complete model of the soil domain, thus allowing the possibility to split the structural model from the soil response. Within this approach, the entire foundation–soil system is replaced by a single element that is placed at the base of the superstructure and aims at reproducing the nonlinear soil–structure interaction effects taking place at the foundation level. Consequently, this element exhibits a non-linear ''constitutive law'', which links some generalized force parameters to the corresponding kinematic ones. It represents a practical tool that allows for efficient dynamic analyses of structures with consideration of non-linear soil–structure interaction effects arising at the foundation level. After a proper calibration, it can be considered as a more refined alternative to the linear elastic approach used in this report, able to capture the nonlinear elasto-plastic behavior of the soil and avoiding the frequency dependency of stiffness and dashpot elements.

The most complete approach is constituted by the "direct method", in which the structure is modelled together with the soil domain. The complete model needs to be able to accommodate for an accurate description of the wave propagation and radiation phenomena (the second arise as waves emanate from the foundation towards infinite extremities of the soil medium), inevitably implying that fully nonlinear dynamic analyses in the time domain for three-dimensional configurations remain beyond the reach of conventional computational capacities, in addition to requiring a very detailed calibration of the model parameters. For these reasons, such an approach does not seem suitable for the regional scale being addressed here.

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