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DYNAMIC SOIL-STRUCTURE INTERACTION EFFECTS ON THE PERFORMANCE OF BASE ISOLATION TECHNIQUES IN BUILDINGS

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Abstract

Base isolation is a well-established strategy for seismic protection, achieved by inserting highly deformable and energy-dissipating devices at the foundation level to decouple the structure from ground motion. However, conventional design approaches often overlook the influence of soil-structure interaction, which can substantially alter the foundation input motion and the deformation patterns of the overall system.
The present research aims to incorporate soil-structure interaction effects into a comprehensive design methodology, to enhance the seismic performance of base isolation systems and prevent adverse outcomes arising from coupled dynamic responses. As a first step, a preliminary analysis on a benchmark study is presented involving a well-documented base-isolated building, in which the interaction with the foundation soil is explicitly considered. Nonlinear dynamic analyses are carried out using the numerical environment OpenSees, simulating the nonlinear and frequency-dependent features of the coupled soil-foundation-isolators-structure system.

Keywords: seismic soil-isolator-structure interaction, nonlinear & inertial effects, multidirectional seismic motion, OpenSees.

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1 INTRODUCTION

Base isolation is a consolidated strategy for seismic protection, based on the insertion of bearing devices with high horizontal deformability and enhanced damping properties between the foundation and the superstructure. This technique can effectively reduce the ductility and deformation demand for the structural members by shifting the fundamental period of the system beyond the dominant frequencies of ground motion, thereby filtering out most of the seismic energy [1-2].

Despite the remarkable potential of base isolation solutions, their conventional design often relies on the oversimplified assumption of a rigid, non-deformable foundation—commonly referred to as the fixed-base assumption—which free field ground motion is directly applied to. Hence, the soil region participating in the dynamic response of the structure is disregarded, which can instead influence the deformation modes, inertial and dissipative patterns of the entire layout. As a result, soil-structure interaction can lead to a seismic response of the isolation system that diverges significantly from that taken as a reference in current design, potentially diminishing the intended mitigation capacity of the isolation system [3-4].

Soil-structure interaction is typically regarded as beneficial for structural performance, due to its tendency to elongate system's vibration periods and increase overall damping. However, it can also produce adverse effects, including: i) foundation rocking that couples translational and rotational deformation modes; ii) additional inertial effects, e.g., in structures with embedded basements; iii) nonlinear soil behaviour, especially under strong ground shaking. Recent studies have demonstrated that these effects can not only impair structural performance, but can even compromise the effectiveness of protection devices designed to mitigate seismic hazard effects [5-10].

In this view, the present study discusses the preliminary results of a benchmark investigation of soil-isolators-structure interactions under seismic loading. This is accomplished through the development of an integrated numerical model relating to a well-characterised, base-isolated reinforced concrete building, capturing both frequency- and amplitude-dependent features of soil-structure interaction through a practice-oriented macroelement-based modelling approach. Multidirectional seismic motions are considered, and a systematic comparison is presented between the fixed-base (FB) and deformable-base (SSI) structural configurations. Special attention is given to salient dynamic interactions that can undermine the effectiveness of the isolation system.

2 CONCEPTUAL FRAMEWORK

The dynamic behaviour of base-isolated structures is the result of the complex interplay between three subsystems: the superstructure, the isolation devices, and the soil-foundation layout. In conventional fixed-base interpretative models the seismic input, typically composed of the sole horizontal components, is directly applied to the isolators. However, when soil-structure is taken into account, the foundation input motion becomes a response of the model itself. In fact, the soil-foundation system typically exhibits a distinct nonlinear and frequency-dependent multiaxial response altering the seismic energy transferred to the structure and its dominant deformation modes.

From a numerical modelling perspective, the most rigorous approach to simulate this interaction in time-domain dynamic analysis is the so-called direct method, that entails fully coupled soil-structure models providing a unified description of the propagation of seismic waves through the soil and into the structure, therefore implicitly incorporating soil-structure interactions. However, the direct approach, besides the large computational effort, requires non-trivial implementations and interpretations of the results, making it suitable primarily for critical applications or high-stakes engineering problems. In contrast, this study adopts a practice-oriented numerical strategy (detailed in Section 3) aimed at capturing essential characteristics of soil-isolators-structure interaction while maintaining computational efficiency.

Isolation devices, such as elastomeric and friction bearings, can be modelled through non-linear force-deformation relationships, accounting for post-yield behaviour, residual deformations and rate dependency. The properties of these devices are conventionally determined with respect to the fundamental period of the fixed-base structure, with the objective of lengthening the system's resonant periods and attenuating seismic energy accordingly.

Considering the fundamental mechanisms at play, the dynamic response of a soil-isolators-structure system can be thus schematised as the co-existence of the following, inherently coupled primary contributions:

- lateral deformations of the superstructure;
- horizontal deformations of the isolators;
- translational-rotational deformations of the soil-foundation system;
- soil nonlinearity.

This overview highlights the need for a comprehensive numerical representation of the dynamic performance of isolation devices, able to simulate the mutual interaction of the bearings with the soil-structure system while remaining accessible for widespread use in engineering practice and large-scale assessment.

3 BENCHMARK CASE AND NUMERICAL FRAMEWORK

A detailed numerical model was developed in OpenSees [11] to serve as a benchmark for evaluating the impact of soil-structure interaction on the seismic performance of base-isolated systems. The model represents a realistic mid-rise building equipped with a base isolation system and resting on a well-documented deposit of Messina Gravels.

3.1 Structural System

Figure 1 illustrates the superstructure layout, which consists of a regular eight-storey reinforced concrete moment-resisting frame with plan dimensions of 15 × 15 m² and a total height of 24 m. The building is assumed to date back to the 70s and was therefore designed according to technical standards in force at that time, that did not provide detailed seismic design requirements. Each storey has a height of 3 m, while the column cross sections progressively reduce in size with increasing elevation. The floor slabs are modelled as rigid diaphragms to capture the global behaviour under lateral loading. The columns and beams are modelled using nonlinear force-based beam-column elements, enabling a realistic simulation of the member behaviour in the nonlinear regime. The cross-sections are discretised using a fiber-based approach: concrete fibers are modelled using the Kent-Scott-Park constitutive model [12], with distinct parameter calibrations for the confined core and unconfined cover regions; the longitudinal reinforcement is represented by steel fibres exhibiting an elastic-plastic behaviour with strain hardening. For further details on the numerical model, the reader can refer to [9].

3.2 Isolation system

The base isolation system consists of a series of High-Damping Rubber Bearings (HDRBs), modelled using zero-length (ISO) macroelements with bilinear hysteretic behaviour. Each isolator exhibits an initial stiffness, a post-yield stiffness, and a yield force, consistent with typical HDRBs used in real applications. In particular, the horizontal elastic stiffness of the devices is obtained by assuming a fundamental vibration period of the isolated structure equal to 3s, in line with technical standards. Then, a constant damping ratio of 15% is assumed for each isolator, as an initial assumption of interest for conventional isolators that will be more accurately analysed in subsequent applications. The total number of isolators and their placement at the base level ensure a uniform lateral response under horizontal excitation. In the vertical direction the isolators exhibit a highly stiff response.

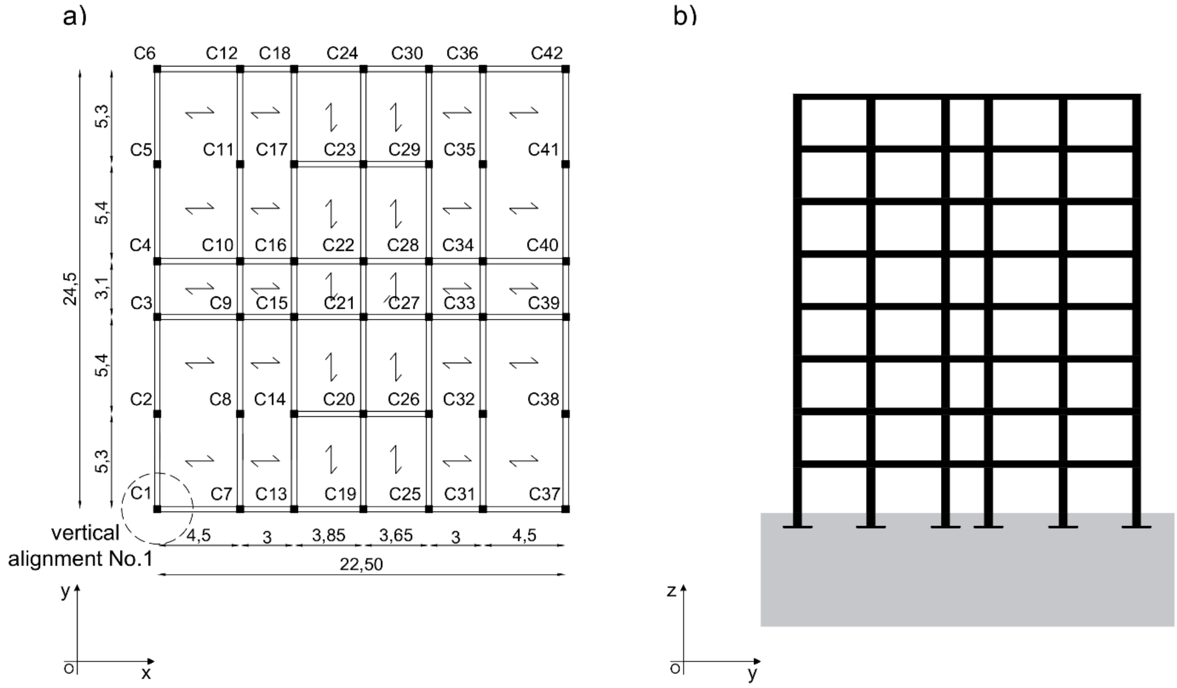

Figure 1. a) Plan view and b) vertical section of the RC frame structure.

3.3 Soil-foundation system

The building is assumed to be located in the high seismicity region of the Messina Strait (Italy). The soil domain is inspired by the subsoil conditions of the area, extensively studied in previous works [13-14]. The equivalent shear wave velocity in the upper 30m is equal to 305 m/s, classifying the site as soil category C in European standards. The soil is characterised by a friction angle of 38° and zero cohesion.

To have an efficient, though non-trivial, computational tool applicable in design and large-scale assessments, each shallow foundation and the surrounding soil participating in the structural response are lumped into a single, zero-dimensional soil-structure interaction (SSI) macroelement. The SSI macroelement consists of an assembly of rheological components providing decoupled responses along the three translations and three rotations of the soil-foundation system. Along each degree of freedom, the macroelement exhibits a viscoelastic-perfectly plastic response, and is coupled with a mass representing the effective participating mass of the soil-foundation system in the corresponding deformation mode. The mass is assigned to the contact node between the SSI macroelement and that representing the isolator.

The elastic stiffnesses and participating masses of the SSI macroelement are calibrated using existing solutions [15] to reproduce the fundamental resonance features of each soil-foundation system. The multiaxial ultimate resistance of the macroelement is computed by using the ultimate limit state surface model proposed by Gorini [16], considering the following decoupled loading paths for the soil-foundation system: the upwards and downwards bearing capacities are evaluated independently from the horizontal resistance. For horizontal loading, a constant vertical force—corresponding to the static load transmitted by the superstructure—is assumed. Then, the horizontal load components $Q_{x\text{-}y}$ are increased incrementally along with the relative moments, defined as $Q_{Ry\text{-}x} = Q_{x\text{-}y} \times h_{m,x\text{-}y}$ ($h_{m,x\text{-}y}$ = building modal height associated with the first vibration mode in the x or y direction). Finally, the horizontal limit loads and moments are determined as the corresponding image points on the ultimate capacity surface.

Hence, the base node of each column is connected to the SSI-ISO macroelement. In its current formulation, the macroelement is capable of capturing frequency-dependent behaviour and the attainment of the resistance of the soil-foundation-isolator system, neglecting however some relevant aspects, such as direction coupling, pronounced hardening behaviour and rate dependence. Nonetheless, this modelling strategy is particularly prone to be adopted with more sophisticated constitutive assumptions, preserving a minimal computational demand—an objective of ongoing research efforts.

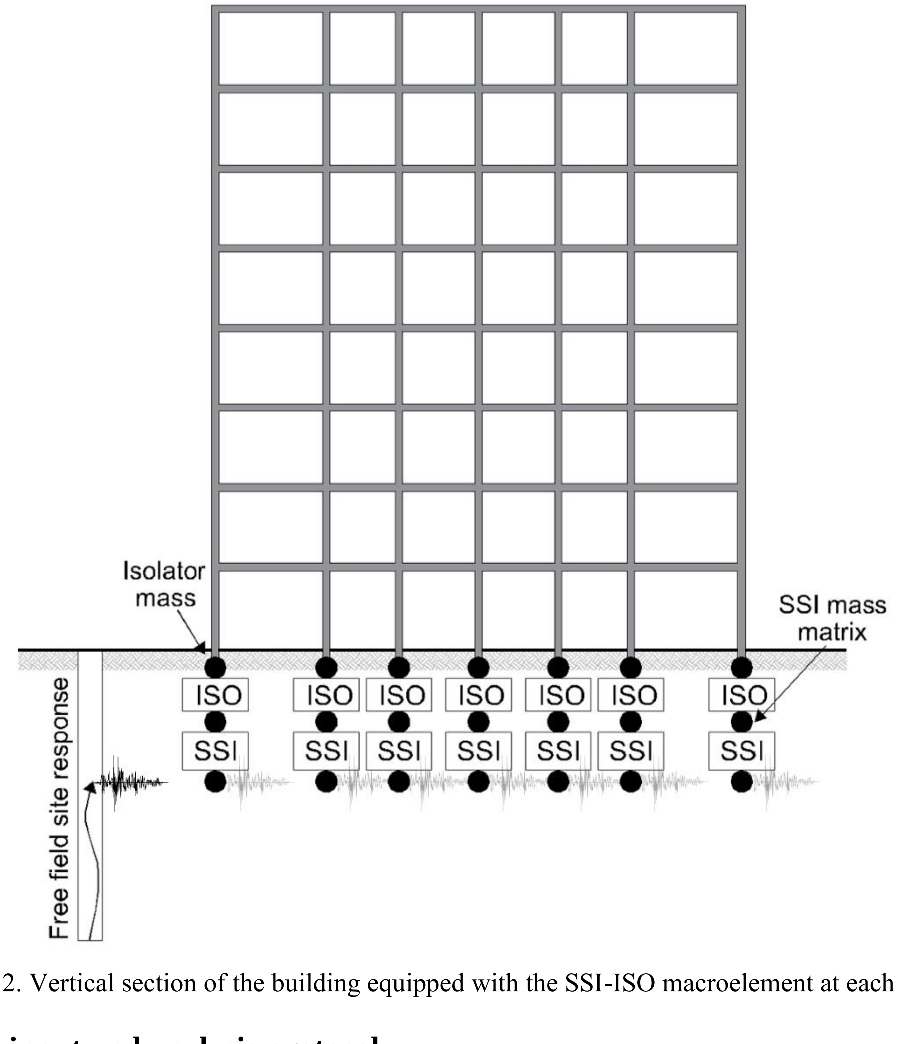

Figure 2. Vertical section of the building equipped with the SSI-ISO macroelement at each support.

3.4 Seismic input and analysis protocol

A staged analysis is adopted, consisting of the initial application of gravity loads followed by the simulation of the seismic excitation. In the seismic stage, the base nodes of the SSI-ISO macroelements are subjected to the horizontal components of the input motion, computed through a separate site response analysis of the considered soil deposit. This input corresponds to the free-field motion computed at a depth equal to the plan width of each footing, representing ideally the lower boundary of the soil region participating to the dynamic response of the structure.

For conciseness, the results discussed herein refer to a representative natural ground motion recorded during the 1989 Loma Prieta earthquake (RSN 765), in California (USA). The record was selected through the web-based PEER NGA-West2 ground motion database (https://ngawest2.berkeley.edu/) and scaled by a factor of 1.25 for compatibility with the target response spectrum at the Near-Collapse Limit State of the case-study building. Detailed information on the selected record is provided in [9].

Time-domain dynamic analyses are performed using an unconditionally stable Newmark-β integration scheme (β=0.25, γ=0.5). The response of the entire system is tracked throughout the analysis, with particular focus on isolator hysteresis, foundation rocking, residual deformations and the formation of plastic hinges in the superstructure members.

4 RESULTS AND DISCUSSION

With reference to the seismic scenario described in Section 3.4, the seismic performance of the isolation system is evaluated by comparing the considered building equipped or not with the isolators, and for each case accounting or not for soil-structure interaction effects (FB vs SSI models, respectively). The preliminary results of this study are illustrated in terms of the maximum interstorey drift computed for the diagonally opposite edge alignments, No. 1 and 2 (see Fig. 1).

Figures 3 and 4 show that the isolators successfully reduce the peak drifts when soil-structure interaction is neglected. When the latter is instead considered (Figure 5 and 6), the structural system undergoes a different deformation pattern. By comparing the FB and SSI models without isolation, it can be inferred that, in the specific case under examination, soil-structure interaction influences quite significantly the drift demand for the superstructure members. The variation is indeed primarily localised in the upper storeys, with an increment of the maximum drift of about 50%.

Interestingly, in the base-isolated configuration, soil-structure interaction leads to a pronounced amplification of the maximum interstorey drift across all levels. The interaction with soil modifies also the dominant deformation modes, as the main discrepancies between the base-isolated FB and SSI models are concentrated in the lower 4-5 storeys. This distinct result can be ascribed to the combined effect of the soil compliance and foundation rocking, which can adversely interfere with the sliding behaviour of the isolation system, thereby impairing its effectiveness in decoupling the structure from ground motion.

Similar results were found with reference to the ability of the base isolation to reduce the maximum seismic-induced shear forces transmitted to the superstructure. Hence, contrary to conventional design assumptions, soil-structure interaction may significantly undermine the seismic performance of base-isolated buildings.

5 CONCLUSIONS

This study presented a preliminary investigation into the effects of soil-structure interaction (SSI) on the seismic performance of base-isolated structures, through nonlinear dynamic simulations carried out using OpenSees. The analysis of a benchmark soil-building system equipped with base isolation highlighted some key features of this interaction:

- Compared to conventional design/assessment overlooking the interaction with soil, SSI can significantly alter the seismic-induced drift demand of the isolated structure; the extent of this alteration is strongly influenced by the multidirectional nature of the ground motion.

- Soil-isolator-structure interaction can affect the deformation modes of the entire system by increasing horizontal deformability and inducing substantial foundation rocking; these effects, in turn, impair the ability of the isolation system to effectively filter the seismic energy transferred to the superstructure.
- Neglecting SSI in the design of isolation systems can result in unconservative estimates, highlighting the need for an SSI-driven design methodology; the development of such framework is currently underway within the present research group.

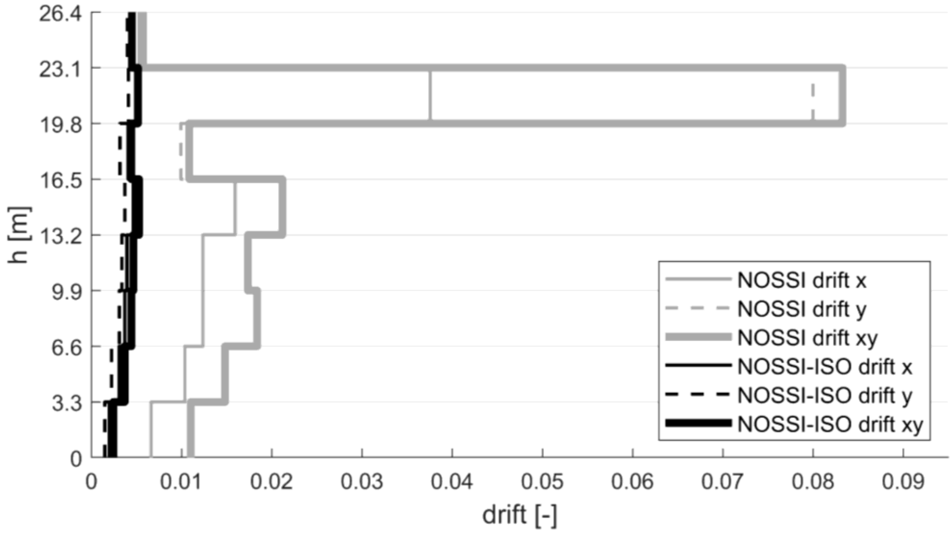

Figure 3. Maximum interstorey drift ratio of Alignment 1 (see Fig. 1) with (ISO) and without base isolation, neglecting soil-structure interaction.

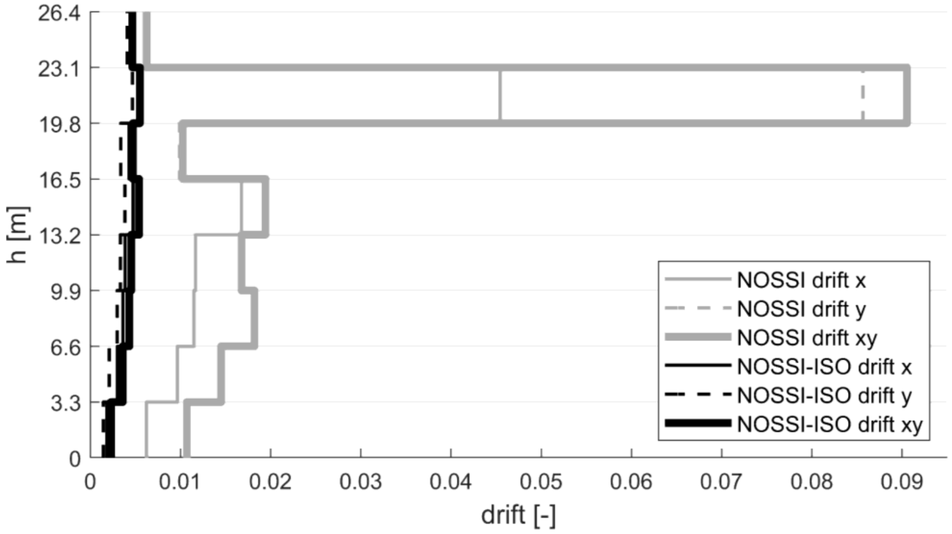

Figure 4. Maximum interstorey drift ratio of Alignment 2 (see Fig. 1) with (ISO) and without base isolation, neglecting soil-structure interaction.

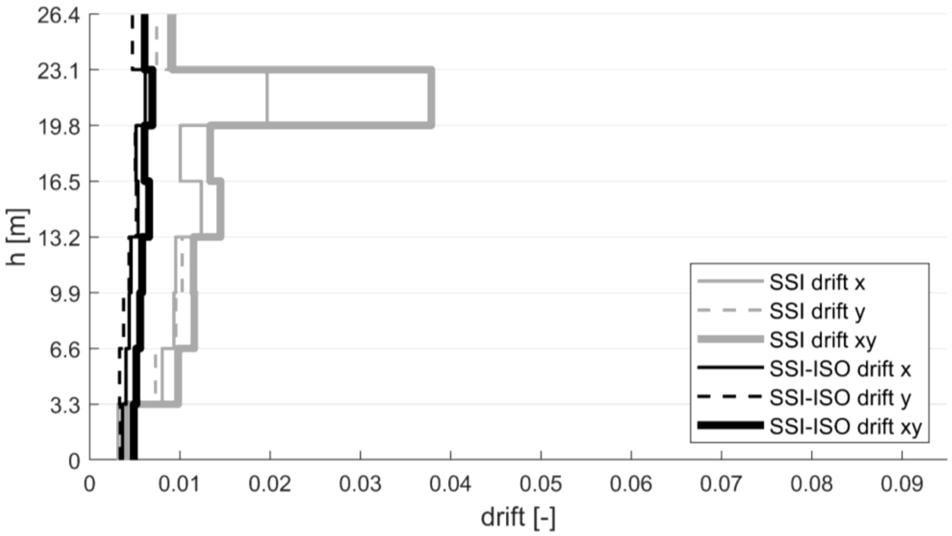

Figure 5. Maximum interstorey drift ratio of Alignment 1 (see Fig. 1) with (ISO) and without base isolation, accounting for soil-structure interaction.

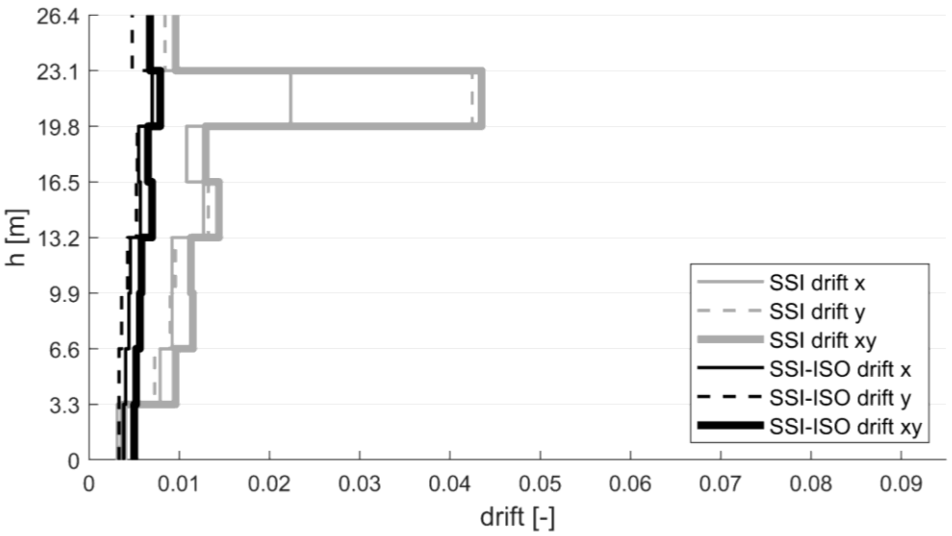

Figure 6. Maximum interstorey drift ratio of Alignment 2 (see Fig. 1) with (BI) and without base isolation, accounting for soil-structure interaction.

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