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Seismic ground reaction forces of rectangular underground structures: Insights from shear container model experiments using an aluminum-rod model ground

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ABSTRACT: Underground structures with rectangular cross-sections are subjected to racking deformation during earthquakes owing to the shear strain of the surrounding soil. Evaluating soil–structure interactions is therefore essential in seismic design. These interactions are strongly influenced by the shear stiffness ratio, which is defined as the ratio of the shear modulus of the structure to that of the soil. However, only a few experimental models have directly measured these interactions. In this study, shear container experiments were conducted to investigate the ground reaction forces acting on rectangular underground structures during earthquakes. The model ground comprised stacked aluminum rods that enabled two-dimensional experiments to reproduce the nonlinear behavior of medium-dense granular sand. It was constructed inside a shear container measuring 1500 mm in width and 800 mm in height, where seismic ground displacements were simulated by imposing shear deformation on the container sidewalls. A rectangular box model with a height and width of 200 mm was embedded at the center of the container to simulate the underground structure. The box model was designed to enable stiffness adjustments, and experiments were conducted over a broad range of shear stiffness ratios. Load cells were installed on all the surfaces of the box model to measure ground reactions. The shear and normal forces acting on the box exhibited minimal dependence on the box stiffness, whereas the eccentric moments, derived from the differences between the normal forces at two positions on each surface, were strongly affected by the box stiffness.

1 INTRODUCTION

Underground structures are completely surrounded by soil; therefore, in their seismic design, proper evaluation of the interaction between the structure and surrounding soil is essential (Wang, 1993; Wood, 2007).

Rectangular underground structures, such as cut and cover tunnels, possess relatively large internal spaces. Consequently, the influence of inertial forces is minimal, whereas that of ground displacement is dominant. Thus, during earthquakes, these structures are subjected to racking deformation owing to the shear deformation of the surrounding soil.

The seismic behavior of rectangular underground structures is primarily governed by the shear stiffness ratio G_s/G_g, which is defined as the ratio of the shear modulus of the structure (G_s) to that of the ground (G_g). This stiffness ratio varies widely among railway cut and cover tunnels in Japan, ranging from 0.05 to 80 (Yamakado, 2023).

For instance, Nishioka and Unjo (2002) derived an approximate equation representing the relationship between the strain transfer ratio (the ratio of the shear strain of the structure to that of the surrounding soil) and the shear stiffness ratio. They demonstrated that this approximation closely reproduced the results of the finite element analyses of rectangular underground structures in which the ground was modeled as an elastic medium.

Most previous studies that focused on the shear stiffness ratio employed analytical approaches, whereas few experimental investigations have been conducted using soil materials that exhibit nonlinear behaviors.

Therefore, our research group conducted experiments to examine the effect of the shear stiffness ratio on the interaction between a rectangular box model and the surrounding soil during earthquake-induced soil deformation (Shimada, 2022a, 2022b; Nishino, 2023; Nanasato, 2024, 2025). In these experiments, shear deformation was applied to the model ground using a shear container in which a box model with arbitrarily adjustable shear stiffness was embedded. The model ground comprised an aluminum rod mass as a two-dimensional granular material that reproduced the nonlinear stress–strain relationship and positive dilatancy characteristics of medium-dense sand (Hirakawa, 2023).

Sliding behavior was observed on the surfaces of the box model in previous experiments. Hence, in this study, experiments were conducted under the same experimental conditions as those in the previous study, except that projections were added to the box model surfaces to suppress sliding. The ground reaction forces acting on the box model were subsequently analyzed.

2 OVERVIEW OF THE EXPERIMENTS

2.1 Shear Container and Model Ground

Figure 1 shows the experimental apparatus used in this study. The shear container possessed a pair of rigid sidewall frames spaced B_g = 1500 mm apart with pin hinges at both the top and bottom ends. Simple shear deformation was applied to the model ground using loading jacks installed 800 mm above the base of the sidewalls.

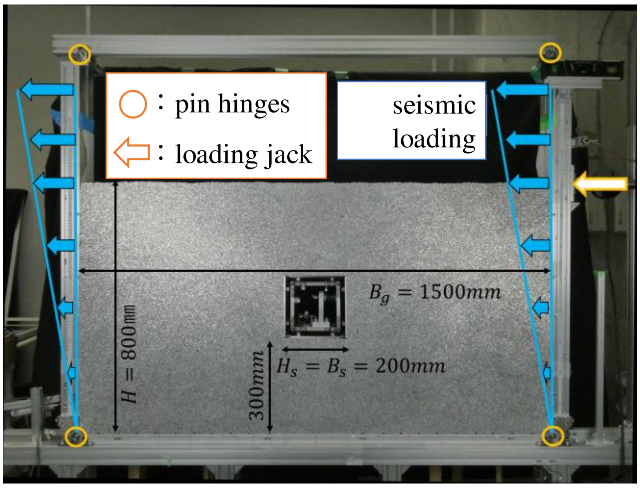

Figure 1. Experimental apparatus

The model ground was 800 mm high, and a box model of height 200 mm, width 200 mm, and depth 150 mm was embedded at its center. The model ground comprised stacked aluminum rods, each 150 mm long with diameters of 1.5, 2.0, and 3.0 mm, mixed in a weight ratio of 1:1:1, with a resultant unit weight of 21.4 kN/m^3. The aluminum-rod model ground exhibited strength and deformation characteristics, along with positive dilatancy behavior, similar to those of medium-dense sand. With the top surface remaining free, monotonic horizontal loading was applied in the leftward direction using loading jacks to induce shear deformation of the ground, which caused the sidewall frames to tilt by up to 6% over approximately 10 min.

Even when a uniform simple shear deformation was applied along the outer boundaries of the aluminum-rod model ground using the shear container, it was impossible to generate a completely uniform simple shear deformation throughout the interior of the model ground. Therefore, an experiment was conducted on the model ground without embedding the box model to clarify, using image analysis, the relationship between the shear strain of the natural ground (i.e., free field) at the box location before installation (hereinafter referred to as the shear strain of the ground, γ_g) and the tilt angle of the container sidewall frames, $\theta_{container}$. An approximate expression for the relationship between $\theta_{container}$ and γ_g is presented in Eq. (1):

$$\gamma_g = 0.5 \times \theta_{container} \quad (1)$$

2.2 Box Model and Experimental Cases

The outline of the box model used in this study is shown in Figure 2. The box model was designed such that the aluminum top and bottom plates and the left and right sidewalls were connected by pin hinges, forming a mechanism that enabled the racking deformation of the box.

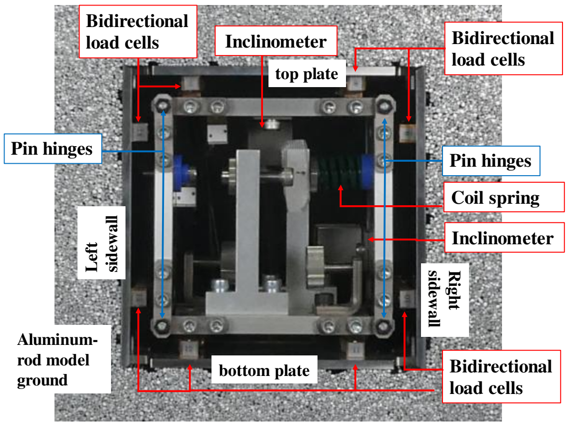

Figure 2. Outline of the box model

Box models with smooth surfaces were used in the previous experiments. Conversely, the box model employed in this study (Figure 3), was provided with projections on all four surfaces to reduce the sliding behavior of the surrounding soil at the box–ground interface. Each projection was 3.0 mm high and 5.5 mm wide. A total of 12 projections were installed vertically at 40 mm intervals on each sidewall, whereas ten projections were installed horizontally at 40 mm intervals on both the top and bottom plates.

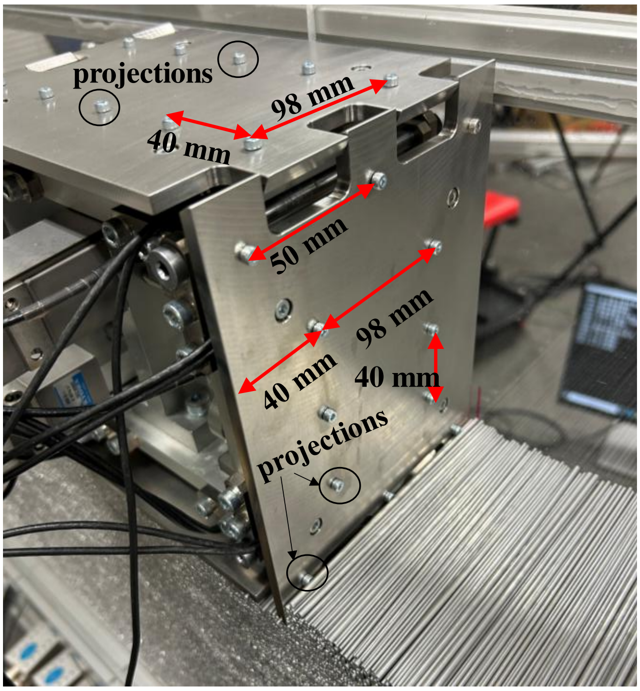

Figure 3. Rough surface of the box

The shear strain of the box model (γ_s) was calculated from the inclination angles of the sidewall (θ_{s1}) and bottom plate (θ_{s2}), which were obtained using servo-type accelerometers installed on the right sidewall and bottom plate. The positive directions of both the inclination angles and shear strain were defined as counterclockwise, corresponding to the deformation direction of the container sidewall frame (Figure 4). The shear strain of the box was then calculated as $\gamma_s = \theta_{s1} - \theta_{s2}$.

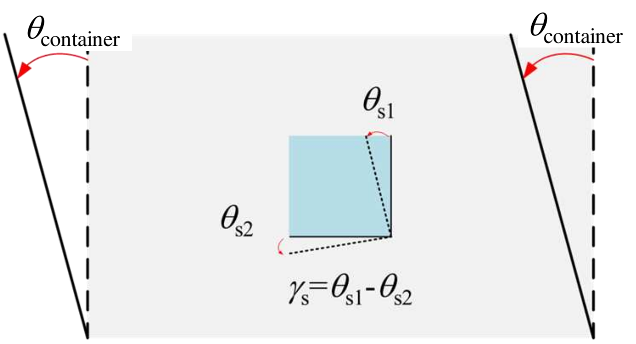

Figure 4. Positive direction of the shear strain

Two pairs of bidirectional load cells were attached to each of the four surfaces of the box model to measure the surface shear (S_i) and normal (N_i) forces. In addition, the eccentric moment (M_{ei}) about the center of each surface was calculated from the difference in the normal forces measured at two positions on the same surface. The positive directions of these forces and moments were defined as those that produced positive racking (pure shear) deformation of the box (Figure 5). These forces are referenced such that the state before the model ground is constructed—when the box model does not contact the ground on any surface—is set to zero, and the values after the model ground construction are used as the initial values prior to loading.

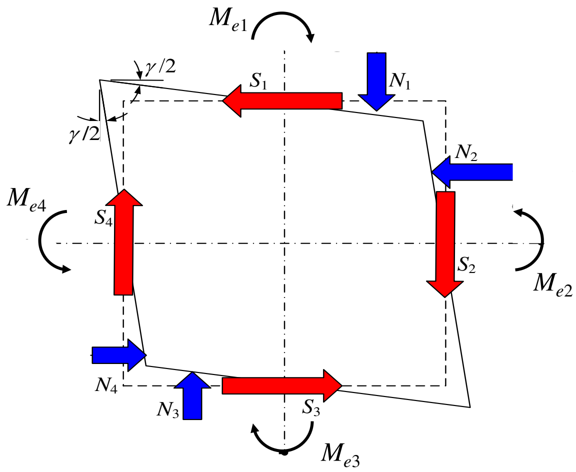

Figure 5. Positive direction of the ground reaction forces

Three experimental cases with different box rigidities were prepared based on the structure of the box model described above: **Case-Rigid**, **Case-Medium**, and **Case-Flexible**. **Case-Rigid** represents the condition under which rigid plate was securely attached to the box using screws, restraining the racking deformation of the box (see Figure 6b). **Case-Medium** represents a condition under which a single coil spring was installed inside the box to resist racking deformation (see Figure 2). **Case-Flexible** represents a condition under which neither plate nor a coil spring were used (see Figure 6a), enabling the box to deform almost freely during racking, although some sliding resistance remained at the pin hinges.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Displacement of the Box Model and Surrounding Soil

The displacements of the box model and surrounding soil were analyzed using image-based tracking. The results are presented in Figure 6. For clarity, only the results for **Case-Flexible** (Figure 6a) and **Case-Rigid** (Figure 6b) are shown. The tracking results correspond to the moment when the shear strain of the ground γ_g reaches 2.0%. The dotted red line in Figure 6 indicates the initial position of the box.

Leftward displacements were observed in both cases. However, in the region above, and including the box model, the displacement in **Case-Flexible** was larger than that in **Case-Rigid**. This indicates that the rigidity of the box model significantly affected the displacements of the box and the surrounding soil.

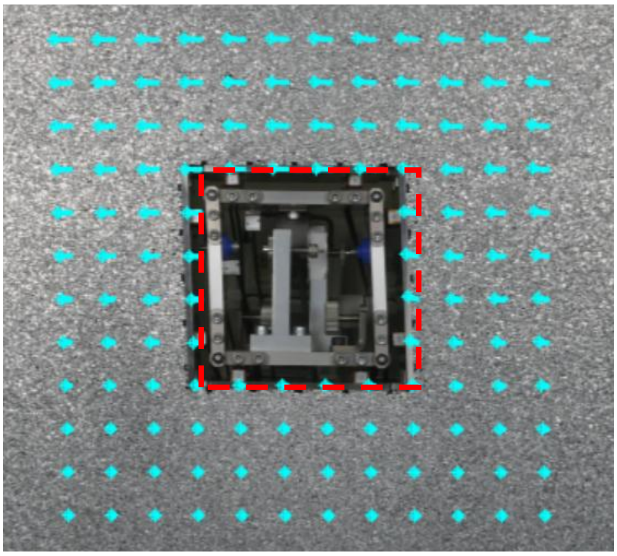

Figure 6a. Ground displacement locus around the box in Case-Flexible

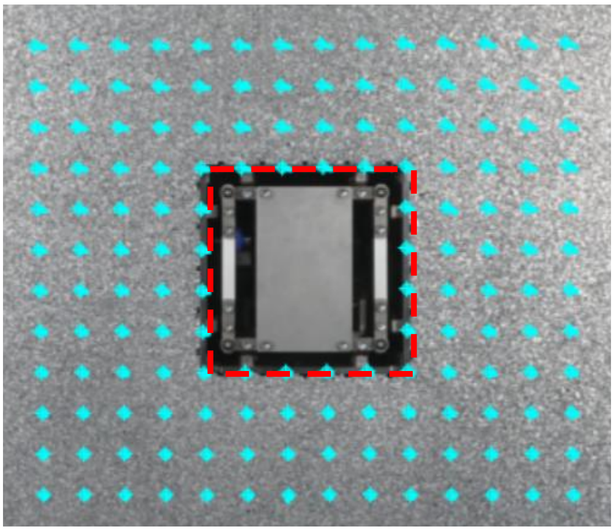

Figure 6b. Ground displacement locus around the box in Case-Rigid

3.2 Racking Deformation of the Box Model

Figure 7 shows the relationship between the inclination angle of sidewall θ_{s1} and the shear strain of the ground γ_g. The sidewall inclination increases as the rigidity of the box model decreases.

Figure 8 shows the relationship between the inclination angle of bottom plate θ_{s2} and the shear strain of the ground γ_g. The bottom plate inclination was directly proportional to the rigidity of the box model.

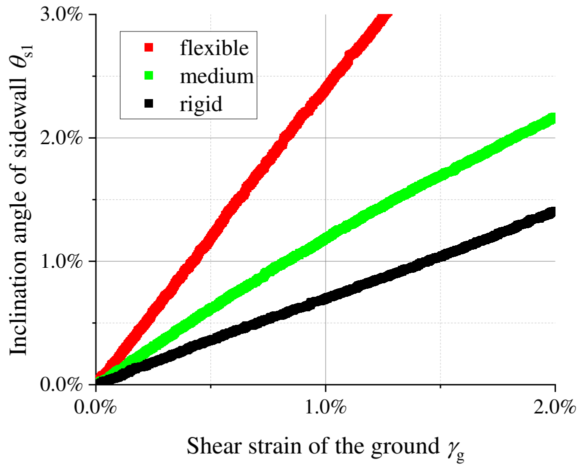

Figure 7. Relationship between the inclination angle of sidewall θ_{s1} and the shear strain of the ground γ_g

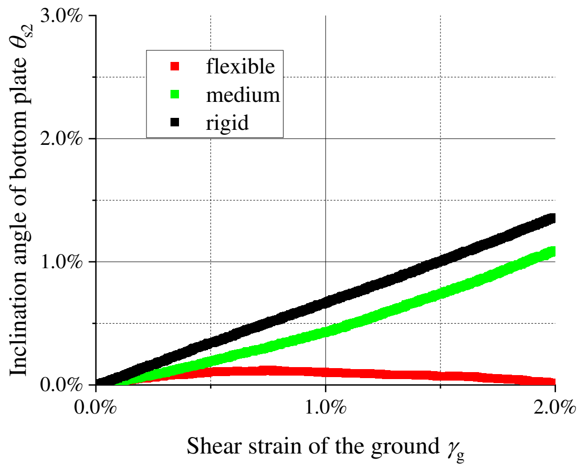

Figure 8. Relationship between the inclination angle of bottom plate θ_{s2} and the shear strain of the ground γ_g

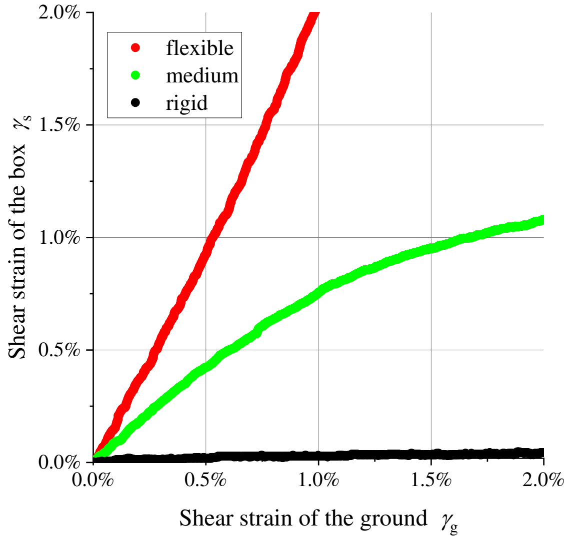

Figure 9. Relationship between shear strain of the box γ_s and the shear strain of the ground γ_g

Figure 9 shows the relationship between shear strain of the box γ_s and the shear strain of the ground γ_g. In **Case-Flexible**, the bottom plate remains nearly horizontal, whereas the sidewall inclines significantly owing to the lateral soil pressure, resulting in large shear strain and significant racking deformation. In **Case-Rigid**, the sidewall inclines under lateral soil pressure; however, because the box is rigid, the bottom plate also inclines along with the sidewall, leading to approximately equal inclination angles of the sidewall and bottom plate. Consequently, the shear strain decreased significantly, indicating that the box underwent a rigid-body rotation. In **Case-Medium**, both the sidewall and bottom plate inclination angles, along with shear strain of the box, assume intermediate values between those of **Case-Rigid** and **Case-Flexible**.

3.3 Ground Reaction Forces of the Box

In this section, the ground reaction forces acting on the box model, including the shear and normal forces and eccentric moments, are analyzed.

3.3.1 Shear Forces

The relationship between the shear forces acting on the surfaces of the box model and shear strain of the ground is shown in Figure 10. All three cases exhibited similar trends across the surfaces. Accordingly, the total shear force on the box appeared to be largely independent of its stiffness based on consistent measurements across the surfaces.

3.3.2 Normal Forces

The relationship between the normal forces acting on the surfaces of the box model and shear strain of the ground is shown in Figure 11. Similar to the shear forces, all three cases exhibited similar trends, indicating that the total normal force was largely independent of the box stiffness.

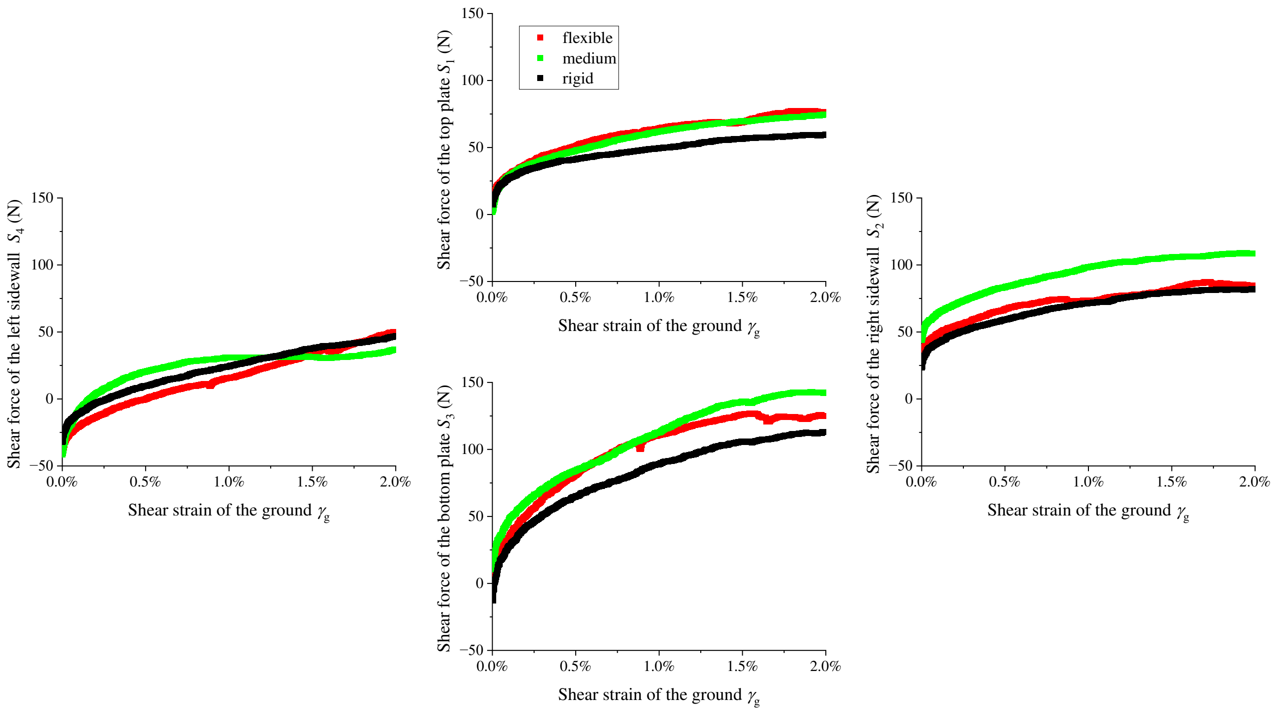

Figure 10. Relationship between the shear forces S_i and shear strain of the ground γ_g

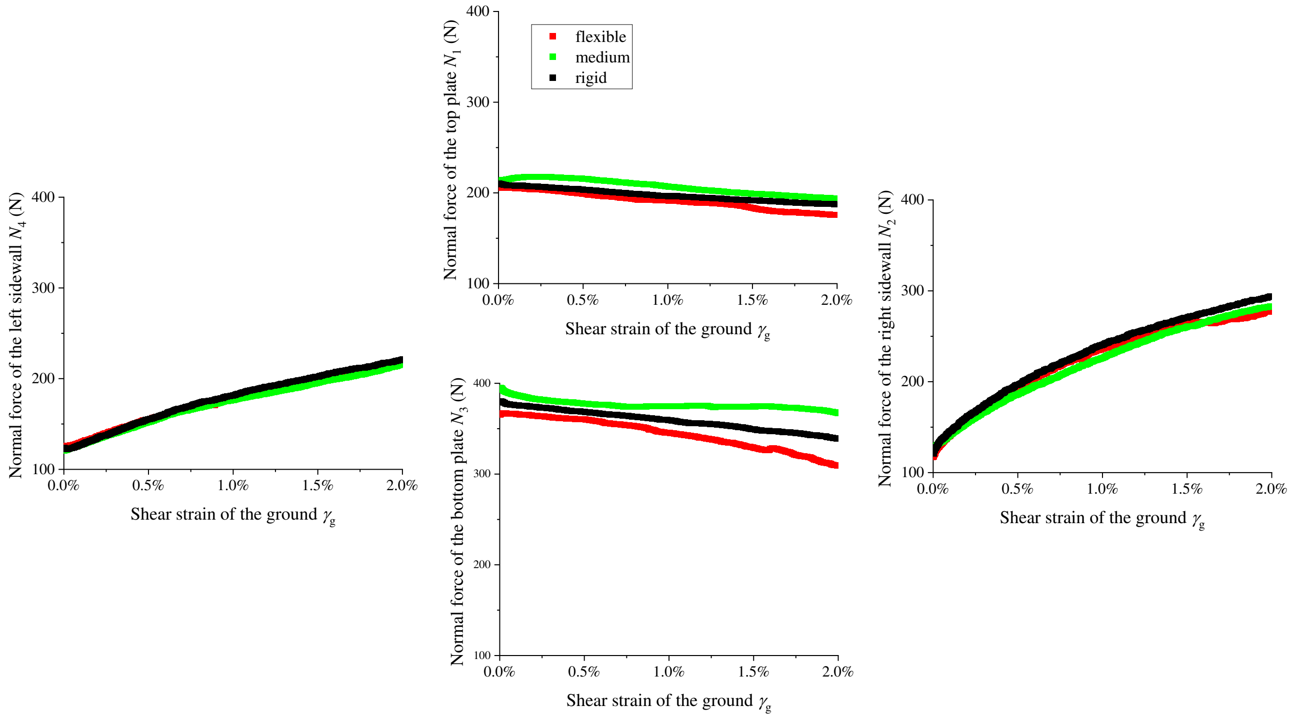

Figure 11. Relationship between the normal forces N_i and shear strain of the ground γ_g

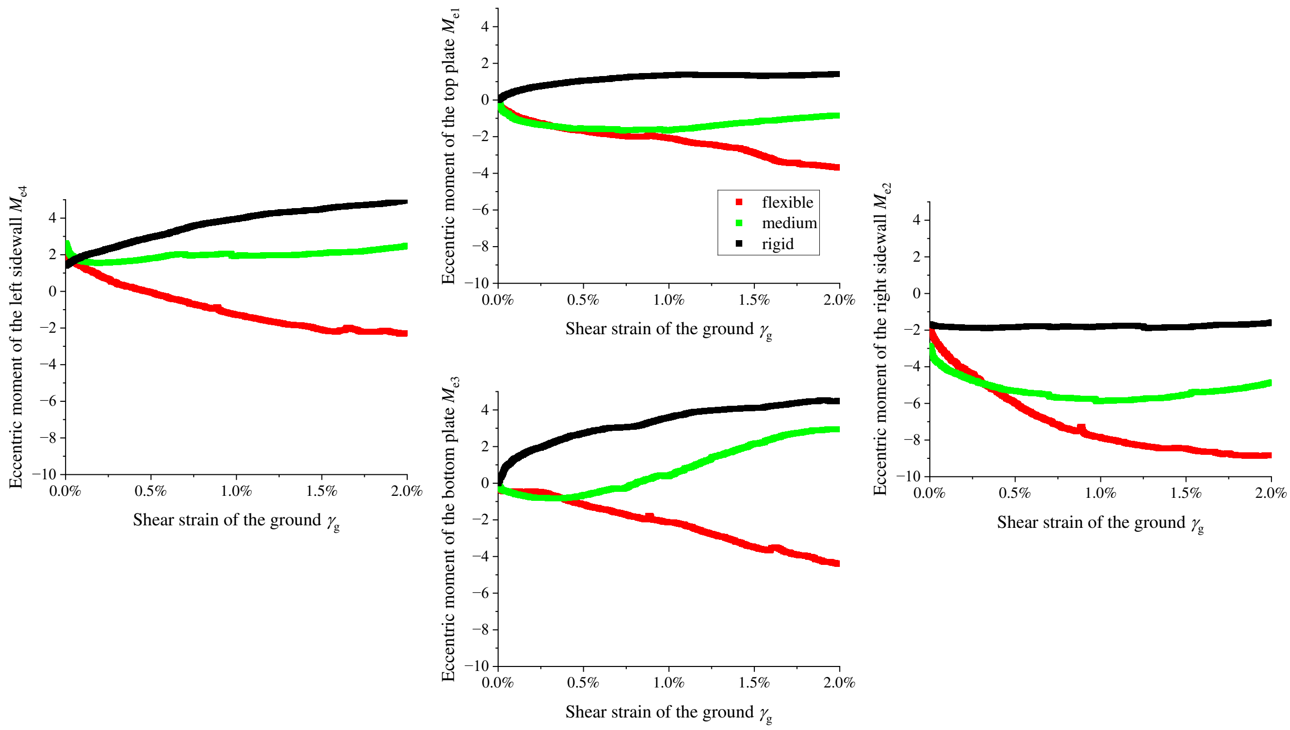

Figure 12. Relationship between the eccentric moments M_{ei} and shear strain of the ground γ_g

3.3.3 Eccentric Moments

Figure 12 shows the relationship between the eccentric moments generated by the eccentricity of the normal forces on each surface of the box and the shear strain of the ground. A negative eccentric moment indicates that the ground reaction force restrains the racking deformation.

A comparison of the three cases for each surface indicated that the eccentric moment was directly proportional to the stiffness of the box. This result suggests that the eccentric moment (i.e., the position at which the normal force acts) is influenced by the stiffness of the box.

Specifically, in **Case-Rigid**, minimal change was observed in the eccentric moments at the top of the plate and right sidewall, whereas those on the bottom plate and left sidewall tended to increase, indicating that the ground reaction force promoted racking deformation. By contrast, in **Case-Flexible**, the eccentric moments on all four surfaces decreased and became negative, indicating that the ground reaction force restrained the racking deformation. In **Case-Medium**, the eccentric moments exhibited both positive and negative values depending on the surface.

4 CONCLUSIONS

In this study, a series of model experiments were conducted to investigate the ground reaction forces acting on rectangular underground structures when shear strain was induced in the surrounding soil during seismic loading. The main findings are summarized as follows:

1. The shear and normal forces acting on the box were not affected by its stiffness.
2. The stiffness of the box significantly influenced the eccentric moment, that is, the acting position of the normal force.

Future work will focus on analyzing the results of this study in more detail and taking scaling laws into account, to gain insights that can be applied more widely in engineering practice. Specifically, we plan to organize the relationship between the shear stiffness ratio and the strain transfer ratio. Since these parameters are dimensionless, they effectively satisfy the requirements of similitude for interpreting 1-g small-scale test results. However, although the aluminum-rod model ground exhibits nonlinear behavior similar to sand, its detailed characteristics, including stress-dependency, do not necessarily coincide perfectly with those of actual soil. Therefore, we will also conduct numerical simulations in parallel to reproduce the experimental results and identify the key nonlinear behaviors essential for predicting responses under real ground conditions.

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