Journal of Geotechnical Geology

Journal homepage: geotech.iauzah.ac.ir

Islamic Azad University,
Zahedan Branch

Behavioral evaluation of soil-based rocking foundations against seismic loading: A review study

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ARTICLE INFORMATION

Received 13 March 2021
Revised 22 April 2021
Accepted 10 June 2021

KEYWORDS
Geotechnics; Rocking foundations; Soil; Surface foundations; Seismic loading.

ABSTRACT

The presented article provides a comprehensive review of rocking foundations and related works. The purpose of review studies is to carefully recognize the related literature to evaluate a particular research question, substantive domain, theoretical approach, or methodology and, in this way, to provide readers with a state-of-the-art understanding of the research topic. In this paper, the viewpoint of significant geotechnical undertaking, methods, techniques and their disadvantages and restrictions are discussed. This assignment focuses on rocking foundation procedure as an important task with performing the high-rise loading platforms on buildings and bridges under seismic conditions with shallow foundations. Giving an introduction to the methodology, the theoretical foundations and background of studies in this field are expressed in this respect. The perspective of this approach is then explored based on the geotechnical aspects of rocking foundations.

1. Introduction

Old bridges are primarily designed for gravity loading by considering minor seismic or lateral loads. These bridges have historically been vulnerable to seismic effects, with multiple cases of damage of superstructure and underground structures, Bridge and in some cases, complete collapse is available. In 1971, the San Fernando earthquake marked a significant turning point in seismic design of bridges and a new set of design standards for bridges began to emerge. Since 1971, bridges designed and constructed according to the design theory that had typically performed well in recent earthquakes. However, studies on non-standard bridges and past earthquakes (McLean and Marsh, 1999) have proven strong trends of deficiency in pre-1971 bridges (Xiao et al., 1996). In comparison to new design philosophy, bridge footing designs from the 1950s to the early 1970s were typically measured using an elastic analysis with little consideration of lateral seismic loads. Such an approach in design led to the construction of foundations consisting of a large (integrated) foundation without considering top and shear reinforcement (Beben, 2020). The real seismic force acting on the footing as a plastic hinge forms in the column may be three to four times greater than the elastic design magnitude. Consequently, many older bridge foundations are likely to have the following inherent potential issues (Kappos et al., 2012).

The concept of rocking foundations for column-footing systems has recently been suggested by researchers. To secure the bridge during seismic loading, A rocking

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https://doi.org/10.30495/geotech.2021.682715

foundation takes advantage of soil failure. As a result, this foundation can act as a fuse, protecting and isolating the bridge structure from severe earthquake damage to some extent. This normally involves under-designing the geotechnical capacity of the foundations (i.e., using foundations with smaller dimensions) and allowing the foundations to be lifted. For instance, the design of the rocking system involves using of a smaller foundation, and consequently transferring the plastic hinges to the soil. In this process, depending on the factor of safety against bearing failure, the mode of foundation failure is either uplift (cases with larger factors of safety) or localized soil failure (cases with smaller factors of safety), and settlement. The use of rocking foundations reduces the ductility demand and also the amount of vibration applied to the columns and superstructures are diminished. The question is whether the soil underneath the foundation or the column should be permitted to fail during seismic loading (Anastasopoulos et al., 2012).

The use of rocking foundations in bridges allows them to rock and uplift so greatly, reducing the seismic forces that must be resisted by the columns and, in many cases, eliminating the need for column-foundation retrofit. According to research, using rocking foundations in competent soils can absorb seismic energy, reduce the need for ductility demand in columns, and improve the foundation systems seismic efficiency. If the flexural capacity of the foundation is less than the flexural capacity of the column, instead of creating plastic hinges in the column, the foundation rotation will occur. Fig. 1 depicts a schematic comparison between conventional capacity design versus rocking isolation (Anastasopoulos et al., 2012; Azarafza et al., 2014; Alemyparvin, 2020). Almost all of the energy in a structure built on fixed supports is dissipated by the inelastic bending behavior of the superstructure components (such as formed plastic hinges). Despite the benefits of using rocking foundations, most of the current design codes and standards are mainly based on the creation of plastic hinges in the structures. However, the numerous advantages of rocking foundations in terms of lowering the cost of repairing damaged bridges following earthquakes have prompted extensive studies in recent years to ensure their performance and to integrate them into the design and development process. This study contributed significantly to the advancement of the concept of nonlinear analysis in performance-based design methods. (Pelekis et al., 2018).

2. Literature Review of Related Works

The behavior of rocking foundations was first observed in the early 1960s and many researchers have proposed it as an effective method of seismic isolation Housner (1963), investigated the free oscillations of a rocking block, determining the rocking time and energy loss. Furthermore, an unexpected scale effect is shown, in which a larger [size] of two geometrically similar blocks is more stable than the smaller one. Using the 'shaking table test' findings, Priestly et al, (1978) confirmed Hausner's relationships for the number of foundations and structures. They conducted a series of small-scale shaking table experiments on systems that allowed uplifting and rotation. The maximum displacement was predicted by their research. In addition, by using the conventional elastic response of the spectrum and the equivalent elastic properties of the system with free rotation; they were able to predict the maximum displacement value and provide simple relationships for designing and evaluating displacements due to rocking.

Psycharis and Jennings (1983) investigated the dynamic behavior of a rocking rigid block supported by flexible foundations which permit an uplift. The continuous elastic foundation with viscous damping (the well-known Winkler model) and a two-spring foundation, in which the structure is supported by two springs and dashpots symmetrically positioned under the base, were both considered in this analysis. In the performed analyzes, the horizontal transfer motion of the structure relative to the soil has been omitted. Also, slipping between the column and the foundation is not allowed. By using the obtained results, they proposed simple solutions to solve the equation of motion and structural analysis for a system with rocking foundation. It was also discovered that the period of rocking motion increases with an increase in the uplift motion and makes the structural system softer. In estimating the earthquake response of structures that function as single-degree-of-freedom systems in their fixed-base state, Chopra and Yim (1985) proposed simpler research procedures to discern the beneficial effects of foundation uplift. For functional structural design, the simplified analysis procedures provide estimates for maximum base shear and deformation to a reliable degree of accuracy. These research procedures are presented for structures supported on rigid foundation soil or flexible foundation soil modeled as two spring-damper components and attached to a rigid foundation mat. Negro et al. (1988) examined a large-scale sand sample. A shallow foundation was modeled in their analysis, which was built on two almost fully saturated soil specimens with relative densities of Dr=45 % (LD) and Dr=85% (HD). The findings are thought to be very reliable, and they can be used to support a variety of investigations into dynamic soil-structure interaction, such as: a) validation of non-linear constitutive models for soil-structure interaction analyses; b) Validation of existing methods for determining the seismic bearing potential of shallow foundations, as well as simpler methods for calculating permanent deformations; c) analysis of the effect of uplift of shallow foundations; d) verification of the currently used formulas for spring and dashpot coefficients of shallow foundations.

Mergos and Kawashima (2005) investigated a 200-meter-long continuous bridge with 5 spans supported by 2 abutments and 4 reinforced concrete columns and situated on sandy layer with their bottoms resting on gravels. The soil used in this experiment had a standard penetration value (N-value) over 50.

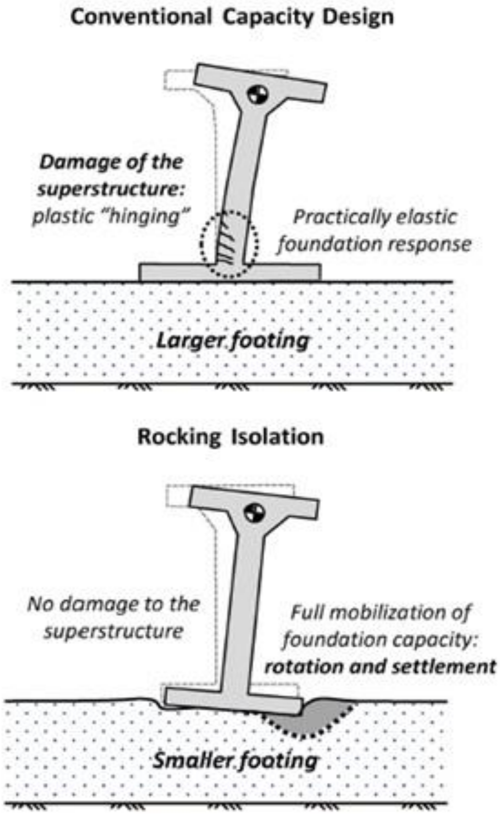

Figure 1. Comparison of bridge base behavior with and without rocking foundations (Anastasopoulos et al., 2012)

The effect of the foundation dimensions was studied using a parametric approach in this analysis. Mergus and Kawashima studied the geometric form and dimensions of a bridge in Fig. 2. The following are the research's most important findings (Mergos and Kawashima, 2005):

- The maximum uplift in the corner of the foundation is 0.2 meters and the separation of the foundation from the underlaid ground occurs up to 95% of the total area of the footing. During the excitation, however, there is no jumping of the footing.
- As a result of softening of the moment versus rotation hysteresis of the foundation, if the foundation separates from the subsoil due to rocking behavior, the plastic deformation of the column at the plastic hinge will be reduced. Consequently, the inelastic rocking of the foundation leads to a separation response in the bridge.
- Under biaxial excitation of the bridge, the isolation effect of the inelastic rocking of the spread foundations is intensified in comparison to uniaxial excitation. Displacements that are caused by foundation rocking, foundation uplifts and underlying soil reactions increase significantly under biaxial excitation.
- The optimal effect of biaxial excitation on the isolation effect of rocking base is determined by the ground motion records characteristics.
- The isolation effects of inelastic foundation rocking are unaffected by the vertical seismic component. This is also the case for deck displacement due to the foundation rocking, footing uplifts, and soil reactions.
- The amount of uplift is reduced by increasing the size of the rocking base. In addition, as the moment capacity of the foundation increases, the potential for failure and damage to the column increases as well. As a result, when the size of the foundation increases, there occurs a decrease in isolation effects on the foundation rocking.
- Soil reaction is constrained by the yield strength of the soil underneath the base as it yields. In this way, as the yield strength of the underlying soil reduces the moment that can be moved to the base of the pier decreases and the isolation effect of inelastic rocking of the foundation increases. However, yielding of the soil results in settlement of the underlying ground, which, in turn, causes residual tilt of the footing.

Espinoza and Mahin (2006) conducted a laboratory study of the rocking action of bridge piers. Physical modeling was used in this research including shaking table experiments. The 6-inch column diameter used in the experiments is proportional to the geometric scale factor of 4.5 and is used as a starting point for calculating other parameters. The used model of tests is shown in Figure 3(a). Figure 3(b) also includes images of model samples produced for research. Their findings showed that the use of rocking foundations to withstand seismic loading provides reliable efficiency when compared to foundations placed on fixed bases.

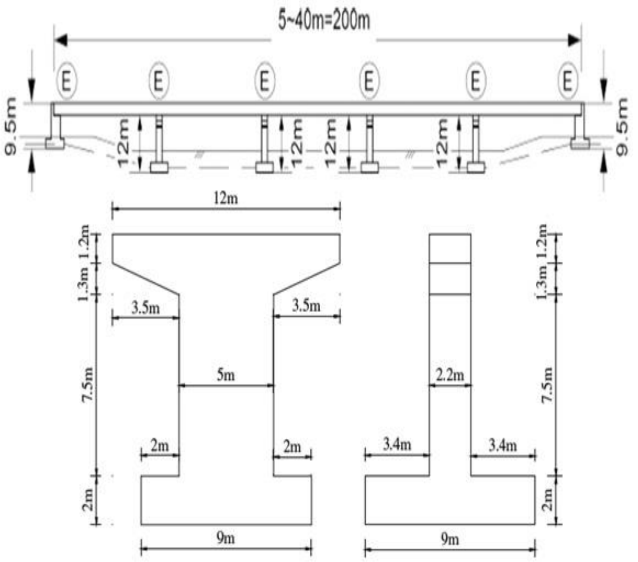

Figure 2. Geometric shape and dimensions of a bridge analyzed by Mergos and Kawashima (2005)

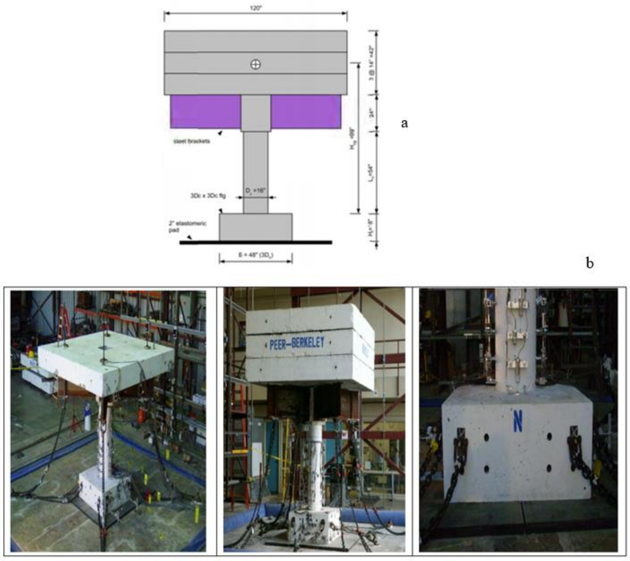

Figure 3. (a) Geometric shape and dimensions of an analyzed model, (b) Laboratory-made samples (Espinoza and Mahin, 2006)

Kawashima and Nagai (2006) evaluated a 10 m high bridge located on the surface under a three directional excitation. It is shown that the effect of rocking seismic isolation is significant in reducing the plastic deformation of the columns at plastic-hinge regions although this increases the deck and columns response displacement. The most important results of research are:

- Due to the increased separation of the foundation from the subsoil as a result of the rocking response, the plastic deformation of the column at the location of the plastic hinge is significantly reduced, which is mainly due to the softening of the moment against the rotation hysterics of the foundation. However, as the isolation effect results in an increase in response displacement of the bridge, the size of footing has to be properly selected in design.
- For a spread foundation which is designed based on a conventional static seismic design using the lateral static acceleration of 0.2 g and working stress design approach rocks separating from the underlying ground when the bridge is subjected to the JMA Kobe near-field ground motion. The amount of uplift on the sides of the foundation for the bridge with a height of 10 meters and under the 1995 Kobe, earthquakes in the range of 80 to 130 mm were recorded. This means that the rocking isolation should have occurred similarly for previous large earthquakes although it was not detected in the past earthquake inspection. Positive use of the rocking isolation brings benefit in seismic design of bridges.

Gajan and Kutter (2008) performed several centrifuge experiments to model and investigate the behavior of rocking foundations on sandy and clay soils stratums during slow lateral cyclic loading and dynamic shaking. The ratio of footing area to the footing contact area required to support the applied vertical load (A/Ac), related to the factor of safety with respect to vertical loading, is correlated with moment capacity, energy dissipation, permanent settlement measured in centrifuge and 1 g model tests. Results show that a footing with large A/Ac ratio (about 10) possesses a moment capacity that is insensitive to soil properties, does not suffer large permanent settlements, has a self-centering characteristic associated with uplift and gap closure, and dissipates seismic energy that corresponds to about 20% damping ratio. Thus, there is promise to use rocking footings in place of, or in combination with, structural base isolation and energy dissipation devices to improve the performance of the structure during seismic loading.

Harden and Hutchinson (2009) used a method to model the structure-foundation system by means of beam on nonlinear Winkler foundation (BNWF). The study's results are compared to experimental data provided by Kutter and Rosebrook.

Kutter and Jeremić (2010) performed centrifuge tests on models of single-column bridges located on the shallow foundations to investigate the rocking behavior of the foundations. Fig. 4 shows the system used for modeling in centrifuge experiments. The deck is also modeled by the Weston Reinforced Concrete Steel Block by an aluminum pipe with a bending stiffness EI scaled by the EI section of the prototype cracked concrete column. The results of these experiments are used to validate the numerical method (finite elements) and also to model the problem of soil-structure interaction.

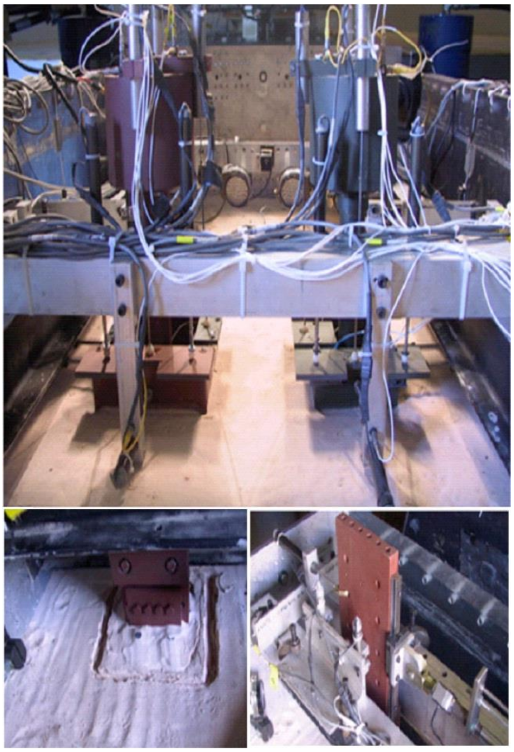

Figure 4. Model structures and connections used for dynamic experiments (Kutter and Jeremić, 2010)

According to the findings of this study, rocking foundations are stable enough to withstand additional loads. Rocking foundations appear to be quite resistant to instability as a result of P-Δ effects, owing to their self-centering characteristics.

Anastasopoulos et al. (2010) presented an approach to design based on the performance of bridge piers. A simple but realistic bridge structure is used as an example in their study to demonstrate the efficiency of the new approach. Two different cases are compared: one with traditional capacity design and an over-designed foundation, resulting in plastic "hinging" in the superstructure, and the other with the new design philosophy and an under-designed foundation, "inviting" the plastic "hinge" into the soil. Static "pushover" analyses reveal that the ductility capacity of the new design concept is an order of magnitude larger than of the conventional design: the advantage of "utilizing" progressive soil failure. An ensemble of 29 real accelerograms is used to investigate the seismic performance of the two alternatives using nonlinear dynamic time history analyses. It is shown that the performance of both alternatives is totally acceptable for moderate intensity earthquakes, not exceeding the design limits. The performance of the new design scheme has been proven to be advantageous for large-intensity earthquakes that exceed the design limits, not only avoiding collapse but also avoiding inelastic structural deformation. It may, however, experience increased residual settlement and rotation, a cost that must be carefully considered during the design process.

Deng et al. (2012) investigated the basic behavior of rocking shallow foundations embedded in dry sand using a centrifuge model test, with various factors of safety for vertical bearing.

according to this study, settlement due to rocking foundations is insignificant in competent soils. Also, a computational method for estimating settlement values is presented in this study. Performed experiences showed that although the base of bridges located on a rigid abutment is damaged by an earthquake of certain intensity, under the same earthquake the base of the bridge located on the rocking foundations will be resistant to failure (Deng et al., 2012).

Johnson (2012) investigated the moment-rotation behavior of rocking foundations on sandy and clay soils using centrifuge and seismic tests. Based on the results, Johnson presented the soil backbone curves used in ASCE regulation no. 41.

By using numerical finite element method, Gelagoti et al. (2012) tried to study the behavior of low-rise structures (one-bay two-story) with two different design schemes (conventional and rocking isolation system) located on competent soil. It is shown that although the performance of both alternatives is acceptable for a moderate seismic shaking, for a very strong seismic shaking exceeding the design, the performance of the rocking-isolated system is advantageous: it survives with no damages to the columns, sustaining non-negligible but repairable damage to its beams and nonstructural elements (infill walls, etc.). In 2014, the American Society of Civil Engineers (ASCE) introduced a new version of the ASCE code 41, which included issues related to rocking foundations. (Hakhamanesh and Kutter, 2016) investigated and validated the parametric design based on ASCE Regulation 41. The criteria of ASCE 41 regulation were also reviewed in the same year (Kutter et al., 2016). The amount of uplifting or permanent settlement is the criterion for initial acceptance of rocking in this standard.

Antonellis et al. (2014; 2015) conducted a series of large-scale shake table tests on bridge columns that were mounted on rocking foundation. It was demonstrated in their experiments that a small-sized surface foundation can significantly reduce the number of destructive forces created at the bridge's base, preventing large amounts of drift and permanent deformation. As a result, it was discovered that using rocking foundations to prevent structural damage is very effective. The maximum possible earthquake drift values that were calculated due to the use of rocking foundations in this study were only 3%. The elevation view of the test setup, as well as the basic geometric characteristics of the soil confinement box, soil, and bridge column specimens, is shown in Fig. 5.

Sharma et al. (2017) performed a snap-back experiment to investigate the moment-rotation behavior in shallow foundations. According to this research, the snap-back test is an effective tool for obtaining an engineering perspective on the nonlinear seismic behavior of surface foundations. In this study, cohesive soil was considered for the experiments, the amount of natural water content was about 30% and the values of plastic and liquid limits were measured at 35% and 75%, respectively. The chosen footing was a rectangular spread footing measuring 1.5 meters by 1 meter. A steel tabular column and a concrete slab at the top of the column were also used to support the superstructure. Vertical loads were added to the top of the structure by concrete slabs (2×2×0.3m) to achieve various factors of safety against bearing failure. During the experiment, the foundation and column displacements were measured. An accelerator was placed on top of the structure to measure acceleration, and strain gauges were attached to the bottom of the column to measure moment during rocking.

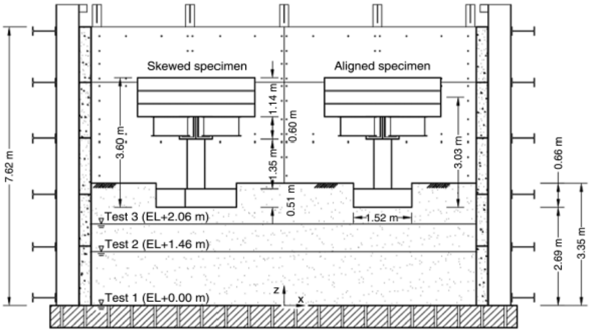

Figure 5. elevation view of the test setup and geometric characteristics (Antonellis et al., 2015)

The snap-back tests were carried out by using chains attached to a quick release mechanism to pull the structure to a specific drift ratio. On the north side of the structure, chain was secured around the top of each column and fastened to an excavator using a quick release mechanism. The excavator was used as an anchor point for the chains. At the desired rotation, the device was released and the structure would rock under free vibration.

Ko et al. (2018) attempted to investigate the behavior of embedded rocking foundations under three different slenderness scenarios. In order to observe the soil-rounding phenomenon and its effects, they used a horizontal slow cyclic test. The soil used in this experiment was a sandy soil. According to this study, the overturning moment tends to a critical value of the foundation's bending capacity as the contact surface of soil and foundation approaches a critical value. Since (footing area/critical surface area) A/Ac=10 is an appropriate value in the design of rocking foundations to balance the permanent deformation and energy dissipation, this study emphasizes the rocking mechanism of the soil-foundation system with A/Ac=10. The results of the experiments show that different slenderness ratios result in different shapes of the soil surface. The final flexural capacity of the rocking foundation is also determined, as well as the effects of soil-rounding. Some of the research terms used in this paper are defined as follows:

- Slenderness ratio: The height of the structure divided by the length of the foundation.
- Soil rounding: The contact area between the foundation and soil is reduced by deformation of the soil-foundation interface, which is called soil rounding (Gajan et al. 2005; Kokkali et al. 2015). Soil rounding, generated by the foundation rocking behavior, can dissipate the applied seismic energy to a soil-foundation structure system and reduce the seismic load on the superstructure (Shirato et al. 2008).
- Ultimate moment capacity: The side soil earth pressure was found to increase the shallow foundation's ultimate moment capacity, which was confirmed by comparing the side soil earth pressure with the overturning moment. At the critical state, the shallow foundation has the minimum contact area and is subjected to an overturning moment equal to its ultimate moment capacity.

Taeseri et al. (2018) has mostly studied Small-strain foundation response analytically, with limited experimental verification against 1g physical model tests. In this study, numerical modeling was used in addition to physical modeling (centrifuge experiment). The effect of two parameters, embedment ratio (D/B) and factor of safety against vertical static loading as the main variables was investigated in 51 centrifuge tests. Finally, the laboratory results were used to validate the numerical method. Namdar et al. (2019) used numerical modeling to investigate the effects of rocking foundation shapes. The numerical analysis results showed that the shape of the foundation has a great effect on the seismic response, revising internal interaction, enhancing damping ratio, improving load carry capacity, revising failure patterns, modifying cyclic differential settlement, minimizing nonlinear deformation, and changing cyclic strain energy dissipation of the structure to seismic loads and can change its behavior to a great extent.

Shrestha (2019) conducted an experimental study on two full-scale reinforced concrete columns. The first was a model with real foundation details, while the second was a fixed foundation with no soil-structure interaction. To compare the performance of the retrofitted columns under the rocking effects, the subsoil was constructed using special foam and simulated in a realistic way. Two layers of 3-inch (75 mm) thick foam were overlaid on hard ground over which the specimen was squeezed with the specified axial load and allowed to rock on the foam before the test specimen was placed and the axial load was applied. This study showed that the use of rocking foundations can greatly reduce drift values.

Kashab (2019) used modeling of rocking foundations with a single-degree-of-freedom system; they investigated the effect of angular load on the behavior of rocking footings. In this study snap-back tests were used. In addition of parametric studies such as damping percentage, natural period, factor of safety against static loading and etc., an analytical method has been proposed for determining the critical contact surface of the rocking foundation and soil. Fig. 6 shows the modeling of a rocking foundation with a single-degree-of-freedom structure to investigate the effect of angular load on the behavior of rocking foundations.

Arabpanaham et al. (2020) used a series of 1 g shaking table tests on three small foundation systems with different embedment depth through applying harmonic waves with three successive increasing levels of acceleration amplitude. According to the results, rocking isolation reduces acceleration transfer to the superstructure during moderate and strong excitation levels for all test specimens.

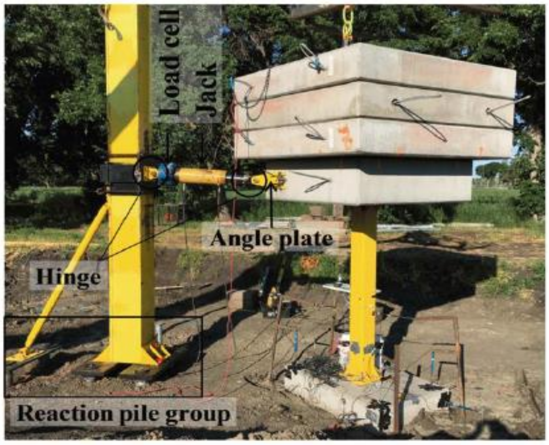

Figure 6. Experiment rocking foot modeling with a single-degree-of-freedom structure (Kashab, 2019)

Furthermore, the experimental results show the difference between the maximum acceleration of the superstructure (in dynamic experiments) and calculated theoretical value was limited for embedded foundations in lieu of static results. The effects of successive excitations on residual rocking stiffness, fundamental period and damping ratio at time instant were also explored. Finally, using the comparisons, it was concluded that the maximum moment observed in the dynamic tests is less than the values of static experiments. To perform these experiments, three different samples were used and the fine-grained Firoozkooh 161 sand with relative density of 50% and mean grain size of 2.7mm was used as well. Due to the greater stability of the sample during shaking, the sand was mixed with moisture of 5% and a silt content of 10%. The samples were considered as single-degree-of-freedom model, which important parameters including lateral stiffness and fundamental period. A constant aspect ratio for superstructure (H/L =3.5) connected to foundations with three different embedment depth ratios (D/B=0, 0.6 and 1.2) was considered in the current study. The most important achievements of this research are (Arabpanaham et al., 2020):

- For the considered three model systems, with the excitation level from number 1 (light motion) to the excitation level 2 (moderate motion), the maximum increase of superstructure acceleration response emerged; however, by changing the excitation level from number 2 to 3 (strong motion), a small increase in the acceleration response of the superstructure occurred as a result of rocking isolation activation for foundations. In addition, for each level of excitation, with an increase in foundation embedment depth ratio, the value of superstructure response increased gently.
- At excitation Level 1, the SDOF response increased relative to the foundation input acceleration for all specimens. Although, significant difference of input and response accelerations occurred at initial cycles. After several cycles, due to the limited nonlinearity at soil-foundation interfaces, the SDOF (system with one degree of freedom) response and foundation input accelerations became closer.
- For surface foundations, the theoretical critical acceleration was close to the maximum experimental acceleration on superstructure. For foundations with embedment depth, difference between experimental maximum acceleration in dynamic condition and theoretical acceleration was higher than one for surface foundations, but milder than those reported by Arabpanahan et al. for static experiments.
- For activated rocking mechanism, increasing the excitation level from 2 to 3 and subsequently increasing the rotational amplitude did not enhance the surface foundation moment and acceleration response of the superstructure, while this change of excitation level for embedded foundation increased superstructure acceleration as well as foundation moment.
- For the three model systems, the backbone curve of the cyclic static response set above the dynamic cycles. This can be due to the loss of contact surface during successive dynamic events and consequently the low moment capacity of the foundation compared to static curves. The second reason for the dynamic response of the foundation was the interaction between shear waves and vertical stresses under the foundation that reduces the bearing capacity of footing with embedment depth in comparison with the static state.
- Adopting from free decay response for specimens with embedded and surface foundations, the instantaneous frequency, f_n, increased with time. This is a rational result, stating that by decreasing the acceleration amplitude (due to damping), thanks to the reduction of foundation rotation and uplift and therefore recovery of the foundation-soil contact area, the system was going to become stiffer and hence, f_n increased and reciprocally, Tn decreased.

3. Development Prospects of Rocking Foundations

The need for effective seismic retrofitting on older bridges after observing poor performance in earthquakes, the experimental findings from large and full-scale structural specimens, and the numerical studies performed are well known. Older column-foundation systems are not designed for seismic loads. Inadequate structural designs include short lap splices at the bottom of the column-foundation, low confinement of the concrete core, very light transverse reinforcement cover the lap-splice region, potentially insufficient dimensions of the foundation and lack of reinforcement steel at the top of the foundation. Lack of transverse reinforcements in the columns leads to unreliable shear resistance, and the design and details of these deficiencies can lead to significant damage of the substructure and insufficient ductility. Various methods have been proposed to improve the seismic performance of the bridge, including increasing the size of the foundations, typically in joints with underpinning, using long dowels, and reinforcement from below. Despite their mechanical efficiency, these techniques are difficult to implement due to limited embedment of foundation and site constraints such as limited access.

4. Behavioral Features of Rocking Foundations

Extensive researches on the structural response of column-foundation scenarios have provided a theoretical and experimental basis for earthquake assessment and retrofitting. In particular, the use of titanium alloy bar

(TiAB) ligaments in combination with TiAB spirals to existing bridge columns has been shown to significantly increase ductility without increasing strength and stiffness. Continuous spirals create additional confinement space over the lap-splice region and core. The supplemental longitudinal TiABs that are anchored inside the column face and foundation create an additional flexural load path to withstand the induced seismic moment and provide dowel-action resistance to resist column sliding relative to foundation. Previous research has shown that TiAB-reinforced columns develop excellent hysterical responses during cycle loading; however, the empirical basis of this reinforcement is generally limited to column/foundation specimens that do not consider soil-structure interaction (SSI) and its effect on the overall response of the structure. In fact, there are no such rigid boundary conditions, and increasing the strength of the underlying structures may transfer forces to the bridge foundation, which does not reflect the actual in situ conditions. These additional forces may damage other parts of the bridge substructure, especially for the old column-foundation and column cap beam, due to the lack of reinforcing steel in these joints.

5. Geotechnical Aspect of Rocking Foundations

Foundation rocking is an alternative method for improving the seismic performance of retrofitted column-foundation systems. Based on the results of rocking tests on “as built” and retrofitted column-foundations in competent soil, if the rocking behavior dominates the response of the system, the column and foundation will remain elastic during shaking and damage is minimized. The rocking foundation provides the system with an alternative hinging mechanism in which a plastic hinge is formed in the retaining soil at its connection with the loaded edge of the foundation. With rocking motion, it is expected to show improved performance in terms of re-centering features, energy dissipation, ductility, and strength maintenance compared to a reinforced concrete column. Rocking behavior depends on various factors such as bridge typology, soil type and density, embedment depth of footing and the presence of water. The results of centrifugal experiments and numerical models show that for bridge systems with two-column bents and pin connections at column-deck connections, rocking foundations improve the seismic performance of the bridge in terms of reducing the relative displacement of the deck (drift) and permanent drift. Soil type was observed to have a very little effect on hysteresis response provided the soil was sufficiently dense (granular soil) or stiff (plastic soil). it has been observed that soil type has little effect on the stress response of rocking foundations. The displacement of a rocking foundation, in terms of settlement or sliding may vary depending on the type of soil. For example, foundations embedded in loose sandy soil may cause a net uplift displacement rather than settlement after seismic loading. The effect of sand in the gap between the subgrade and the foundation upon an uplift cycle can reduce the re-centering of the foundation; on the other hand, this effect may increase energy dissipation. In surface foundations, regardless of soil type, foundation experiences settlement due to rocking. However, lateral loading may lead to sliding of the foundation and resulting in asymmetric hysteresis response. The presence of water and the degree of saturation may also have detrimental effects on the rocking response in the foundation. For example, in saturated or submerged soils, the rocking mechanism may cause water to flow from or inside the gap under the uplifted part of the foundation, leading to soil erosion and tilting of the structure. For a saturated soil layer of loose sand under the foundation, the liquefaction caused by shaking may lead to excessive settlement, which in turn can cause catastrophic damage to various structural components. By reducing the degree of saturation, capillary forces and surface tension at the air-water-soil interface leads to an increase soil strength and improves its deformation response. Accordingly, a foundation is expected to perform better while shaking under these seasonal conditions.

6. Conclusion

In summary, new regulations related to the foundations with shallow rocking motion have been developed as a result of previous researches. However, there is no rational design approach towards column-foundation systems for retrofitted bridges that take into account the combined effects of nonlinearity of structural components and soil. Design questions still need to be answered, such as:

1) Do columns strengthen due to retrofitting which is caused by unintended damage to footings with vintage reinforcing details?

2) Will the resulting seismic settlements and sliding occur within the permissible magnitude?

3) Should rocking and soil failure under the foundation be allowed during loading?

Limited resources require these methods that can utilize soil-structure interactions, allowing the life of existing bridges to extend, and tools to be developed to quickly assess whether retrofit of bridge substructures is preferable over replacement given the existing structural details, substructure type, and soil conditions. Considering the soil-structure interaction may also indicate that retrofit or replacement of the substructure is not necessary. Given the number of bridges that are considered desirable in terms of retrofitting / replacement, the impact on both the budget and the project delivery time can be significant, considering the potentially significant consequences for improving the seismic resilience of the transportation network.

Acknowledgements

The authors wish to thank the Department of Civil Engineering, Tabriz Branch - Islamic Azad University for giving the opportunity for conducting this study.

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