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Rocking Response of a Slightly Embedded Foundation: Effect of Loading Angle

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ABSTRACT

The paper examines the rocking response of a shallowly embedded square footing subjected to 1-D (i. e footing aligned to shaking orientation) and 2-D shaking. The test-case is inspired by the Large Scale experiments performed at the Shaking Table of University of California at San Diego. Once the numerical methodology is validated the paper explores the effect of loading angle β on the overall response of the Soil-Foundation-Structure system. It is concluded that for values of $\beta \neq 0^o$ the 3-d confinement offered by the peripheral trench "walls" is contributing towards increased values of footing capacity against overturning Moment. Moreover, when the footing is skewed by $\beta = 15^\circ$ and $\beta=30^\circ$, the rocking response is coupled with a spinning motion along its periphery. This complex 3D rocking, tends to further stress out the peripheral walls of the trench, producing increased plastistifications that are reflected on the increased values of observed hysteresis. On the other hand, increasing values of β are provoking a clear "humping" of the soil surface right beneath the footing base which is associated with a decrease in the rate of settlement accumulation.

Keywords: Validation with Shaking Table experiments, rocking, square footing, loading angle, settlements

INTRODUCTION

The concept of "rocking isolation" suggests a competitive alternative for foundation design against the code recommendation of "capacity design". According to this new idea, the foundation is intentionally designed to uplift and/or slide before any structural damage is evident on the supporting column. Over the last decade a growing group of researchers (*Paolucci, 1997; Pecker, 2003; Gajan et al., 2005; Pender, 2007' Anastasopoulos et al., 2010, Gelagoti et al., 2012, Anastasopoulos et al. 2013*) have systematically studied the mechanics of rocking footings both analytically and experimentally. Their findings are suggesting that the implementation of this rocking concept bounds the maximum developed moment on the superstructure, thus protecting the latter from seismic motions overly exceeding its capacity.

This paper explores the implementation of rocking isolation on shallowly embedded footings founded on a dense sand layer. The first task of the paper is to validate the implemented numerical methodology my comparing analytical findings with the measured response of a recent Large Scale Shaking Table Test (*Antonellis et al., 2015*). Once validation is established, the research focus is moved on the investigation of the effect of the loading angle β on the rocking response of the Soil-Foundation-Structure (SFS) System.

DESCRIPTION OF THE EXPERIMENTS

To demonstrate the effectiveness of rocking-isolation concept as a means of seismic protection of bridge piers, a series of large-scale proof-of-concept experiments has been implemented. The test series ─ a collaboration between UC Berkeley and UC Davis─ took place at the NEES facility of University of California at San Diego (UCSD). The experiment set-up included (*Antonellis et al., 2015)* two bridge piers (diameter: 1.20 m, height

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7.31 m and deck mass 2320 kN) founded through shallow square foundations (plan view: 5.49 x 1.83 m and height: 1.22 m), on a stratum of clean sand (of D_r = 90%). The specimens were constructed conventionally using common practice materials within the largest implemented rigid confining box in US (internal dimensions: 10.1 m x 4.6 m and height: 7.6 m). Both footings were slightly embedded (depth of embedment over width D/B=0.4), but differ with respect to their orientation: one footing was completely aligned to the orientation of the seismic motion (i. e x-direction), while the other one was placed obliquely by β=30˚. The two specimens were simultaneously subjected to uniaxial excitation (applied in x-direction) consisting of six consecutive seismic motions.

NUMERICAL VALIDATION: SIMULATION OF THE EXPERIMENTS

The numerical model is an exact replica of the actual test case in 1:1 scale. A view of the finite element mesh implemented in the ABAQUS code is portrayed in **Fig. 1.** For the simulation of the non-linear soil behavior of sand, the 8-noded continuum elements (C3D8) follow a "pressure-sensitive" kinematic hardening constitutive model capable of reproducing both the low-strain stiffness and the ultimate resistance of soils (*Anastasopoulos et al, 2010*). The pier is modeled with elastic linear beam elements of circular section, d=46cm, while the deck inertia is accounted by a lumped mass element (of weight W = 250 kN) on the pier top. To simulate the rigid boundaries of the confining box appropriate kinematic constrains have been introduced. Between the soil and the footing elements a no-tension frictional interface is assumed with a friction coefficient of μ=0.7.

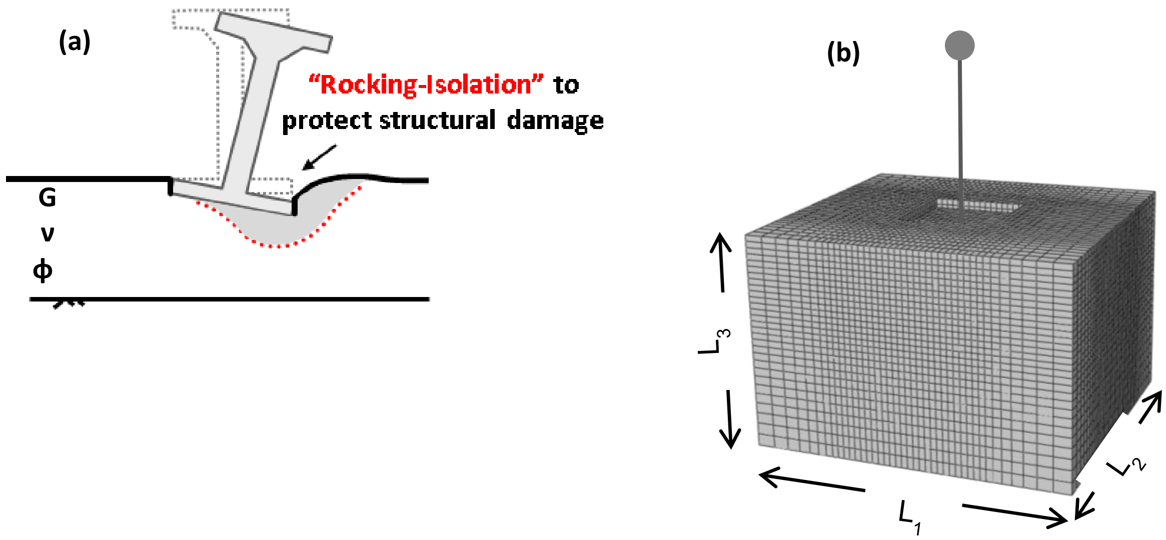

Figure 1. **(a)** Definition of the rocking – isolation concept implemented in a bridge pier. **(b)** The 3d FE model for the simulation of the experimental set-up.

The testing protocol involved a sequence of six (historical) strong ground motions recorded during the famous events of Loma Prieta (1989), Imperial Valley (1979), Northridge (1994) and Kobe (1995). The comparison between the FE-computed and measured (experimental) response is provided in **Fig.2** for two example excitations; the El Centro (Imperial Valley, 1979) and the Pacoima Dam (Northridge, 1994). It is clear that the numerical findings compare well both in terms of overturning moment and rotation, with the measured response. Yet, the numerical model largely overestimates the footing settlements. It is interesting to note that in the experimental set up the maximum settlements after the 6-strong event sequence was approximately a mere 1 cm! A possible explanation for this quite unexpected response is reported in Antonellis et al. (2015) and Hakhamaneshi & Kutter (2016, in print), according to which the excessive dilation and soil raveling during the rocking motion of the footing have led to excessive concentration of soil underneath it which in turn provoked the 'close to zero' settlements of the tested system. Understandably, this experimental-specific response may not be described by the implemented small deformation FE code.

Table 1 Definition of Geometrical and Mechanical Parameters in FE Simulation

Soil Stratum Geometry		
Property	Unit	
Dimension along x axis	L_1 : m	5.03
Dimension along y axis	L_2 : m	4.62
Dimension along z axis	L_3 : m	3.35

Soil Stratum Mechanical Properties		
Property	Unit	
shear modulus	G : MPa	67
Poisson's ratio	ν	0.3
friction angle	ϕ : deg.	43˚

Structure-Foundation System		
Property	Unit	
column diameter	d : m	0.46
footing breadth	B : m	1.52
footing height	h : m	0.51
free height of deck mass	H : m	2.52
deck mass weight	W : kN	250

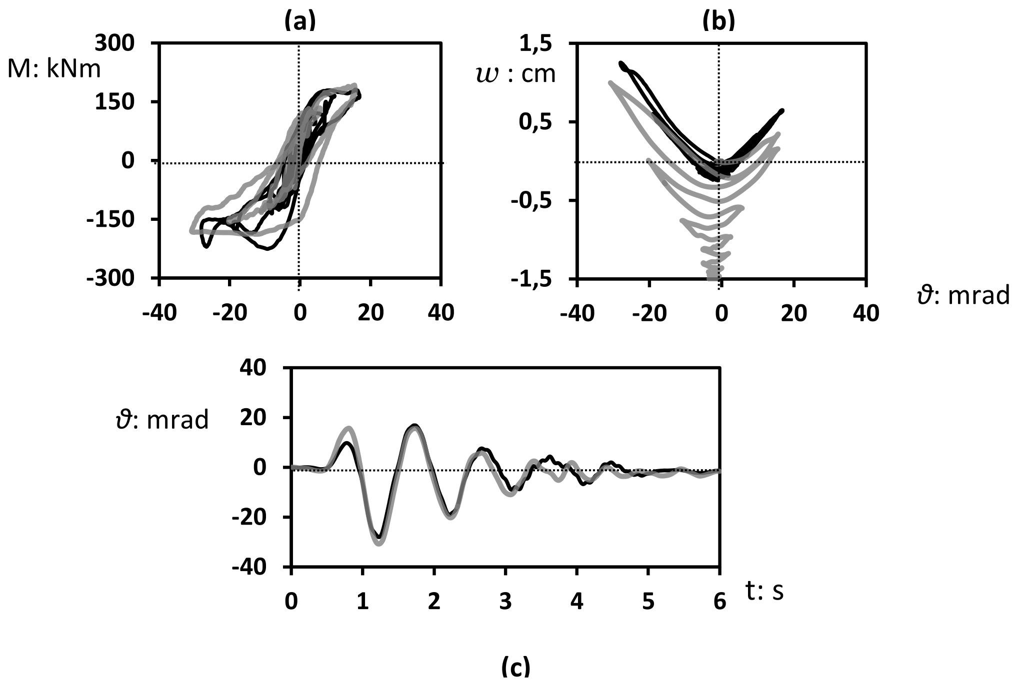

Figure 2. Comparison of the analytical (light grey line) and the experimental (black line) results of the aligned footing in terms of **(a)** Moment-Rotation; **(b)** Settlement-Rotation; and **(c)** Rotation time history, for the fourth motion (Northridge, 1994) of the sequence.

PARAMETRIC STUDY: EFFECT OF LOADING ANGLE

The loading angle, notated as parameter β expresses the obliquity of the input motion with respect to the footing's orientation as sketched in **Fig. 3**. In this set of analyses the angle β varies within a range of a quadrant, taking values: 0˚, 15˚, 30˚ and 45˚. Evidently, for small values of angle β the system is mainly loaded along one of the two horizontal directions, however, as β approaches β =45˚, the system is equally excited along x and y directions. The intermediate values of β (15˚ and 30˚) introduce an eccentricity in the system, in the sense that the resultant force is analyzed in two components that different significantly in amplitude. In this latter case a more complex rocking response is materialized which even includes rotation along the footing's perimeter, as in the case of a spinning coin.

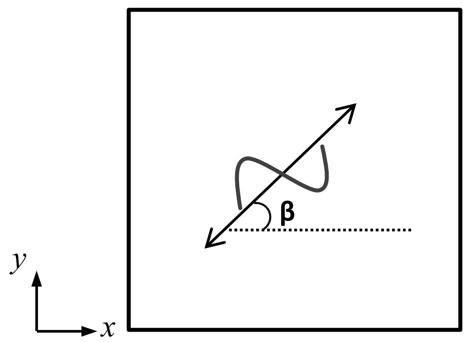

Figure 3. Plan view of the footing: Illustrative definition of the loading angle β

Dynamic Loading

The numerical model is here subjected to two artificial sinusoidal motions of 10 cycles each: a weak motion of A_{max} = 0.15g, f = 2.86 Hz and a strong one of A_{max} = 0.30g, f = 1.43 Hz which is expected to provoke footing uplifting and large rotations. When the system is excited by the weak motion (**Fig. 4**), irrespectively of the β value, the system performs similarly in terms of overturning moment-rotation: the system responds well below its moment capacity, while the nonlinearity is barely visible. Regarding settlements, the response is sinking dominated, accompanied by small rotational values (approx. 3 mrads). Yet a quite interesting trend is observed; as the value of β increases, the residual settlement decreases.

The footing response when subjected to the strong motion scenario is presented in **Fig. 4b**. The grey line indicates the monotonic results from the static pushover analysis, performed by imposing a lateral displacement at the deck-mass. It is evident that In the case of the aligned footing (β= 0˚) the system yields the lower moment capacity. This may be attributed to the 3-D trench effect (portrayed in **Fig. 5**) which tends to enhance the soil restrain and accordingly the foundation capacity as β approaches 45˚. The main difference in the results of the strong motion compared to the weak one is that the system reaches its moment capacity during the first, cycle of the motion, while quite interestingly, the developed moment during the next cycles is much lower. Naturally, the strength of the system has not changed; its stiffness however has slightly declined, due to the created gap between the footing and the walls of the trench. As the footing rocks, lateral resistance in the form of passive stresses from the surrounding trench walls is provided. Once though these walls are deformed, and the trench becomes somewhat broader, the footing fails to find resistance in the surrounding trench for the same rotational values, hence responding with a lower developing moment. In other words, the system behaves momentarily as surface foundation. To corroborate this theory we calculate the moment capacity of the system as it would be without taking into account the contribution of embedment:

$$M_{c,\,foot} = (QB)/2\ (1-1/FS_v) \approx 170\ \text{kNm} \tag{1}$$

where Q is the total vertical load of the structure, B is the footings width and FS_v=29 (measured by Antonellis et al., 2015).

Notably this phenomenon is building up when β=15˚ and 30˚ respectively (**Fig.6**). In this case, the footing executes a complex movement which combines rocking with spinning, during which the peripheral walls are further stressed and the trench is further deformed. This complex 3D rocking movement is further reflected in the shape of the M-θ loops. Evidently, the loops of β=0˚ and β= 45˚ (cases of uniaxial loading) are much thinner than for those produced for β = 15˚ and 30˚, where the footing plastifies more soil as it spins along its periphery.

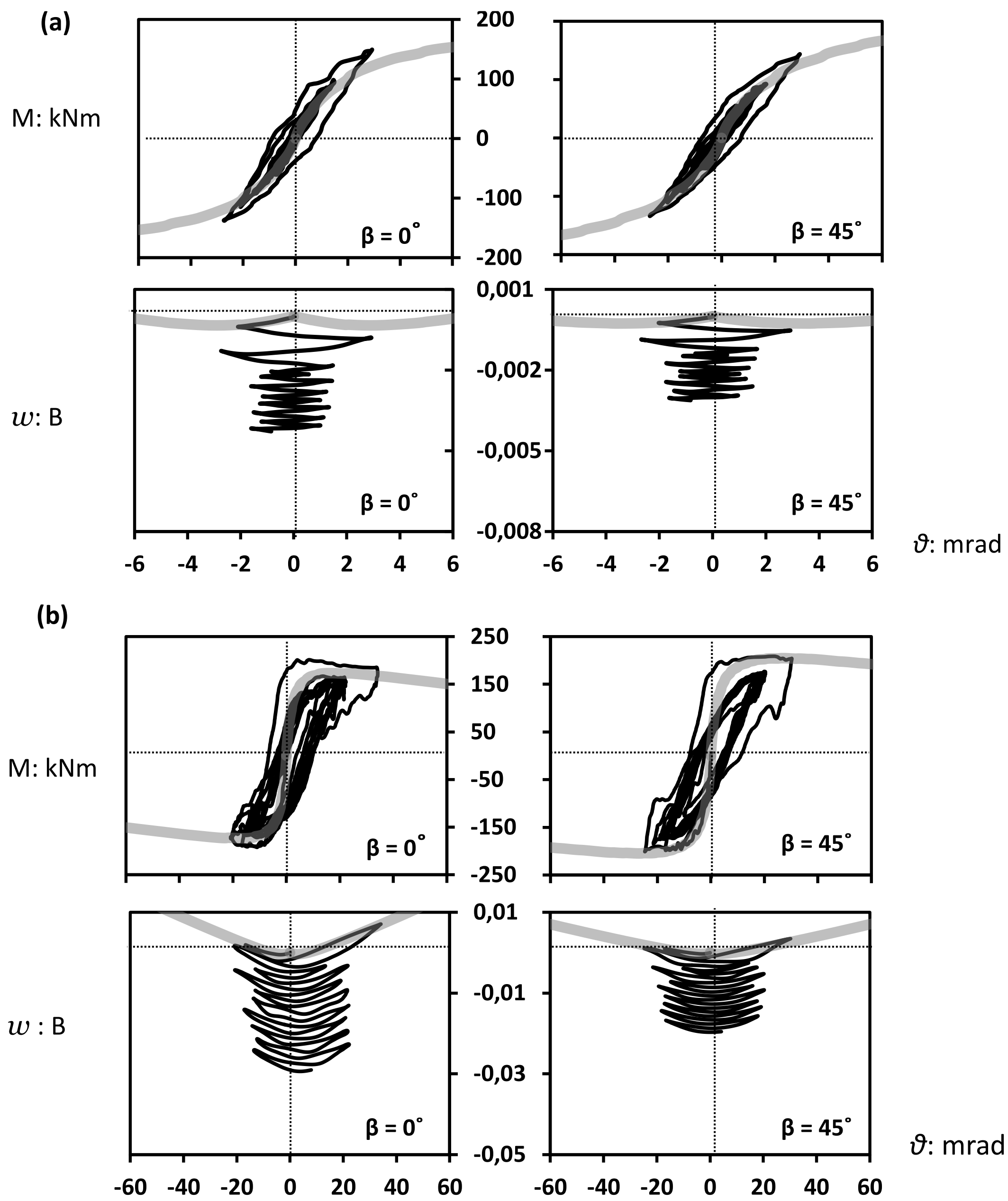

Figure 4. Results from the dynamic analyses utilizing **(a)** the weak sinusoidal motion and **(b)** the strong sinusoidal motion; in terms of Moment-Rotation and Settlement-Rotation

Significant differences may also be observed in terms of settlements. As witnessed by the plots of **Fig. 4(b)**, the value of residual settlement w_{max} tends to decrease as the angle of β increases, leading to the striking difference of 50% between the β = 0˚ and β = 45˚ test cases. The explanation behind this behavior is sought in the developing tractions on the foundation soil. As evidenced by the plastic strain distribution at the instant of maximum rotation ϑ, presented in **Fig. 7**, low values of β lead to a more uniform distribution and lower values of tractions since a larger footing area remains in touch with the soil. On the other hand, values of β closer to 45˚ create an intense concentration of high traction towards the footing edge, almost as if the footing penetrates the supporting soil. The price to pay is the excessive curvature of the underlying soil at the end of the seismic excitation (a phenomenon which has been also experimentally observed in the work of Gajan et al.(2005)).

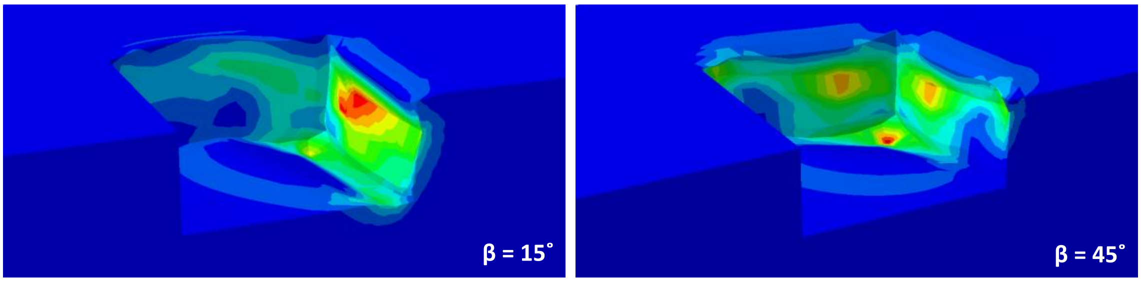

Figure 5. Contours showing the magnitude of plastifications inside and around the embedment trench.

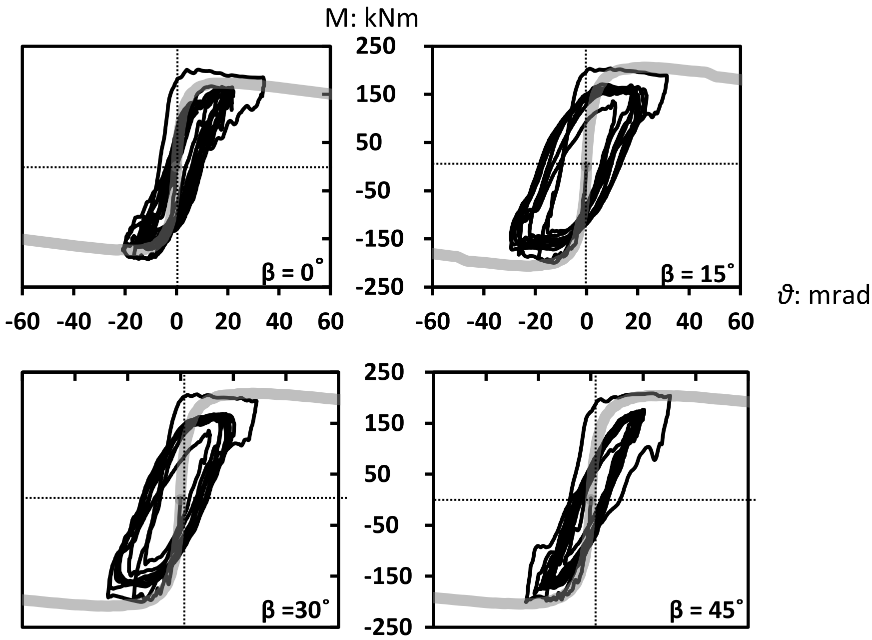

Figure 6. Effect of loading angle β : Moment-Rotation loops

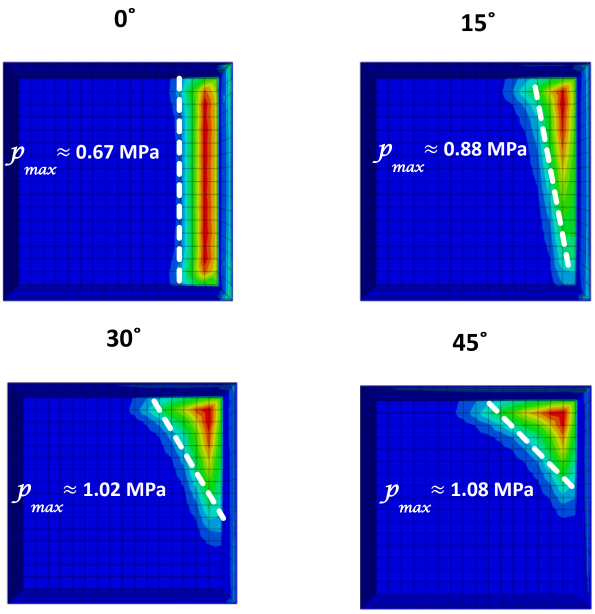

Figure 7. Contours of normal traction underneath the footing during the first cycle of the strong sinus motion.

Evidently, **Fig. 8** depicts the developed humping of the soil-footing interface by presenting the non-uniform distribution of settlements along the half width of the trench (red dashed line). The settlement values are normalized with the value of the soil settlement underneath the footing center. Indeed the normalized settlements at the center and at the edge of the trench are strikingly different for β = 45˚ than for β = 0˚, which directly affects the rate of settlement accumulation: the more rounded the soil surface (β = 45˚), the smaller the area of the footing being in touch with the soil. Consequently a shallower stress bulb will be developed and evidently the settlements tend to be restricted. Moreover, as $\beta \neq 0^o$ the foundation resistance to overturning moment tends to increase as the walls at the corner of the trench tend to obstruct the foundation rotation. The higher the resistance the lower the accumulation of settlement.

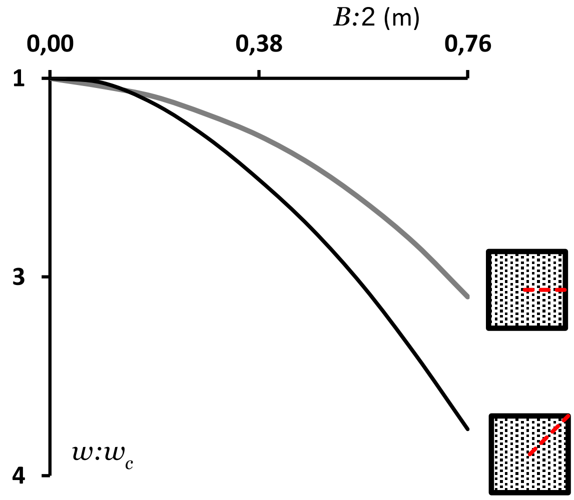

Figure 8. Distribution of normalised settlements along the half footing width (at the end of the initial pulse of the strong sinus motion).

CONCLUSIONS

This paper explores the rocking response of shallowly embedded footings founded on a dense sand layer. The first task of the paper is to validate the implemented numerical methodology my comparing analytical findings with the measured response of a recent Large Scale Shaking Table Experiment (*Antonellis et al., 2015*). Once validation is established, the research focus is moved on the investigation of the effect of the loading angle β on the rocking response of the Soil-Foundation-Structure (SFS) System.

The numerical methodology involves a 3D configuration implemented in the FE code ABAQUS. The entire SFS system is simulated, subjected to the exact testing protocol sequence of six strong ground motions. The analytical results compare very well in terms of M (moment)-θ (rotation) loops with the measured response. Yet the numerical simulation tends to systematically over-predict the actually developed settlements.

The parametric study that followed on the effect of the loading angle β, showed that there is an overstrength in the overturning moment capacity of the footing which is directly associated with the increase in the effective width of the footing, as β approaches 45˚. Moreover the 3-dimension geometry of the trench "walls" is enhacing the foundation confinement thus further contributing to increased capacity values. When the SFS is subjected to a sinus type dynamic loading an interesting phenomenon is observed: the pier attains its (theoretically calculated) moment capacity during the initial cycle of loadings, but as the motion progresses, the capacity drops to a lower values (as if the trench walls stop contributing after the initial cycle). It is believed that during the first cycle the peripheral walls are significantly deformed, and the trench becomes somewhat broader. As a result, in the subsequent cycles the footing fails to find resistance in the surrounding trench for the same rotation, hence responding with a lower moment.

When the SFS is skewed by β = 15˚ and β=30˚, the rocking response of the system is coupled with a spinning motion along its periphery. This complex 3D rocking, tends to further stress the peripheral trench. As such it produces increased plastistifications which are reflected on the broader hysteresis loops (of the M-θ plots). Furthermore, increasing values of β are producing a clear "humping" of the soil surface right beneath the footing base. As a result the footing tends to rock on top of a curved surface and progressively along a fraction of its nominal width. Subsequently as the area of the footing being in touch with the underlying soil decreases, the stress bulbs become shallower and the settlements decrease as well.

REFERENCES

Anastasopoulos I., Kourkoulis R., Gelagoti F., Papadopoulos E. (2012). "Rocking response of SDOF systems on shallow improved sand: An experimental study", *Soil Dynamics and Earthquake Engineering*, 40, 15–33.

Anastasopoulos I, Gelagoti F, Kourkoulis R, Gazetas G (2011), "Simplified constitutive model for simulation of cyclic response of shallow foundations: validation against laboratory tests", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 137(12):1168–1154.

Anastasopoulos I., Gazetas G., Loli M., Apostolou M., Gerolymos N.(2010), "Soil failure can be used for seismic protection of structures", *Bull Earthquake Eng*, 8:309–326

Antonellis G., Gavras A., Panagiotou M., Kutter B., Guerrini G., Sander A., Fox P. (2015). "Shake Table Test of Large-Scale Bridge Columns Supported on Rocking Shallow Foundations", *Journal of Geotechnical and Geoenvironmental Engineering*, 141, 5.

Gajan S., Kutter B., Phalen J., Hutchinson T., Martin G. (2005). "Centrifuge modeling of load-deformation behavior of rocking shallow foundations", *Soil Dynamics and Earthquake Engineering*, 25, 773–783

Gajan S and Kutter BL. (2008) "Capacity, settlement and energy dissipation of shallow footings subjected to rocking", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 134(8), 1129–41.

Gelagoti F, Kourkoulis R, Anastasopoulos I, Gazetas G. (2012), "Rocking isolation of low rise frame structures founded on separate footings", *Earthquake Engineering and Structural Dynamics*, 41:1177–97.

Hakhamaneshi M. and Kutter B (2016), "Effect of Footing Shape and Embedment on the Settlement, Re-centering and Energy Dissipation of Shallow Footings Subjected to Rocking" (in print)

Mergos PE, Kawashima K. (2005), "Rocking isolation of a typical bridge pier on spread foundation", *Journal of Earthquake Engineering*, 9(2): 395–414.

Paolucci,R.,Shirato, M.,and Yilmaz, M.T.(2008). "Seismic behaviour of shallow foundations: shaking table experiments vs numerical modeling", *Earthquake Eng. Struct. Dynam.* 37, 577–595

Pecker A. (2003), "A seismic foundation design process, lessons learned from two major projects: the Vasco de Gama and the Rion Antirion bridges", *ACI International Conference on Seismic Bridge Design and Retrofit*, La Jolla, USA: University of California at San Diego.