Analysis of Concrete Walls under Earthquake Action Influence from different types of Foundation

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Ohrid
30.08-03.09
14 ECEE 2010

ABSTRACT

In these paper concrete walls are examined, and how different foundation changes the wall's behaviour during seismic excitation. Concrete walls are common in Icelandic building culture; the walls are usually founded on gravel bed, but are calculated as they are fixed to the ground, usually no influence from rocking and soil-interaction behaviour are taken into account.

The results show that the difference in motion and energy dissipation is significant between a normally fixed base scenario versus the case where rocking and translation is allowed; the motion increases while stress decreases and the energy dissipation is due to the friction and pounding between the foundation and the support. This leads to much lower concrete stresses in the rocking wall than in rigid one. This is one of the reasons non-reinforced or poorly reinforced concrete buildings in South-Iceland did not heavily damage in recently earthquakes.

Keywords: Rocking, Foundation uplift, Soil-structure interaction, Nonlinear analysis, Squat concrete wall.

1. INTRODUCTION

It‘s common in the field of structural engineering to fix the foundation to the ground while carrying out design calculations. This is done to make calculations easier and to deliver quick solutions for static load cases and design combinations. For such analysis, fixed approach is usually acceptable. However, during earthquakes fixed-ground calculations do not depict the actual behaviour of the structure. The response of soils to earthquake excitation is highly complex and depends on a large range of factors, many of which cannot be established with any certainty. This is the reason that mainly structural calculations are done by fixed model with ground. In addition, if soil-interactions calculations are done it is needed to establish a non-linear model.

It has been shown in the South Iceland earthquakes in the years 2000 of moment magnitude M_w=6.6 and 2008 of moment magnitude M_w=6.3, as lightly reinforced structures on gravel beds escaped with less damage than would have been expected, the earthquake forces having a lesser impact on these structures because of the translation and rocking of the foundations. (Thorhallsson et al. 2009).

When the effect of the South Iceland earthquakes are assessed, and the destruction following in their wake is examined, it can be said that South Iceland came through amazingly well and better than one would have expected. None of the residential buildings collapsed. The buildings most damaged in the earthquakes were older structures, particularly. Special mention should be made of houses built on poor foundations, houses constructed of building blocks made of lava aggregate and houses with floating base slabs resting on fill of poor quality, as well as houses with masonry partitions. Also, a few old poorly built unreinforced concrete and hollow concrete block houses were damaged. However, it can be generally said that well-constructed wood houses and reinforced concrete houses withstood the earthquakes well, sustaining little or no damage. One can also find houses of masonry construction that withstood the earthquakes or sustained little damage despite great excitation. It often appeared somewhat a matter of chance which houses suffer damage (Sigbjornsson, 2002).

2. FORMUALATION OF A SOIL-STRUCTURE INTERACTION

The simulation of the infinite medium in the numerical method is a very important topic in the dynamic soil-structure interaction problems. The general approach for treating this problem is to divide the infinite medium into the near field (truncated layer), which includes the irregularity as well as the non-homogeneity of the foundation; and the far field, which is simplified as an isotropic homogeneous elastic medium (Wolf and Song, 1996). See Fig 2.1.

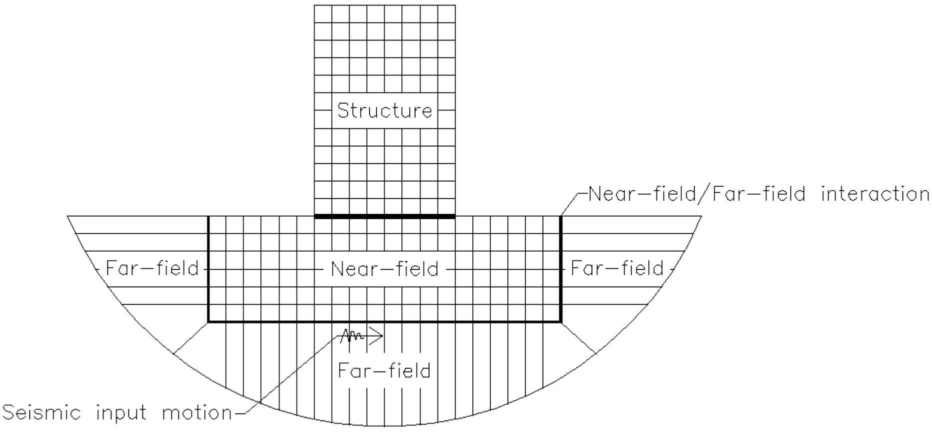


Figure 2.1. A soil-structure interaction system.

The near field is modelled using finite elements, and the far field is treated by adding special artificial boundaries or special connection elements. The soil is in most cases, a semi-infinite medium and this unbounded domain should be enlarged so large to the extent that the simultaneous modelling together with the structure may be impractical. In a dynamic problem, it may be insufficient to prescribe a zero displacement at a large distance from the structure, as it is routinely done in static problems (Nofal, 1998).

2.1 Near-field, finite element method, FEM

The system equations of motion, for typical dynamic and undamped system, can be assembled from the element matrices see Eqn. 2.1:

$$[M]\{\ddot{u}\}+[K]\{u\}=\{R\} \tag{2.1}$$

Where [M] = Mass matrix, [K] = Stiffness matrix, $\dot{\mathrm{u}}$ = Velocity, $\ddot{\mathrm{u}}$ = Acceleration and $\{R\}=$ Load vector.

2.2 Far-field, boundary element method, BEM

To calculate the properties of the boundary condition, it is necessary to consider a plane wave propagating in the x-direction. The forces that cause wave propagation are shown acting on a unit cube in Fig. 2.2.

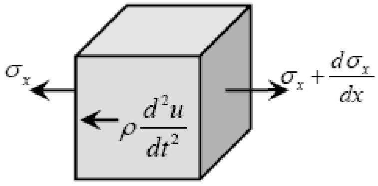


Figure 2.2. Forces acting on a unit cube (Wilson, 2002).

For this cube, the one dimensional equilibrium equation in the x-direction, see Eqn 2.2:

$$\rho \cdot \frac{d^2u}{dt^2} - \frac{d\sigma_x}{dx} = 0 \tag{2.2}$$

Where, ρ = Mass density.
u = Displacement.
σ_x = Stress in the x-direction.

The one-dimensional partial differential equation in the classical wave propagation, see Eqn 2.3:

$$\frac{d^2u}{dt^2} - v_P^2 \cdot \frac{d^2u_x}{dx^2} = 0 \tag{2.3}$$

Where, v_P = P-wave propagation velocity.

Viscous boundary is taken into consideration by well-known equation 2.4. of motion for the system considered in this study can be written for the damping case as:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{R\} \tag{2.4}$$

Where the load vector $\{R\}$ is determined from the near-field/far-field displacements.

Damping matrix Eqn. 2.5 can be written as:

$$C = \begin{pmatrix} A \cdot \rho \cdot v_p & 0 & 0 \\ 0 & A \cdot \rho \cdot v_s & 0 \\ 0 & 0 & A \cdot \rho \cdot v_s \end{pmatrix} \tag{2.5}$$

v_P, P-wave velocity is calculated according to Eqn. 2.6 and v_S Shear wave velocity is calculated according to Eqn. 2.7.

$$v_P = \sqrt{\frac{\lambda + 2 \cdot G}{\rho}} \tag{2.6}$$

$$v_S = \sqrt{\frac{G}{\rho}} \tag{2.7}$$

The values in matrix C are put in MATRIX27 in ANSYS to represent the damping matrix for far-field conditions. It is an arbitrary element without a specified geometry but its response can be specified by stiffness, damping or mass coefficients. The matrix's translationally degrees of freedom are activated for one node while the other node has no function and are fixed, thus negating all forces at the truncated boundaries according to equations 2.5. (Yazdch et al, 1999), (Zhang and Tang, 2009).

3. WALL MODELS

First case is the squat wall is rigidly fixed on the ground (cantilever) as in Fig 3.1. Second case is the squat wall contacted to rock, with and without damping as in Fig. 3.2. Third cases are examined were the squat wall is contacted on one metre thick mean gravel isolation, with and without damping as in Fig 3.2. When the walls are connected to rock and gravel with the contact elements, they are allowed to rock and translate. On the top of the walls is distributed load q= 24,5 KN/m to represent concrete roof or floor.

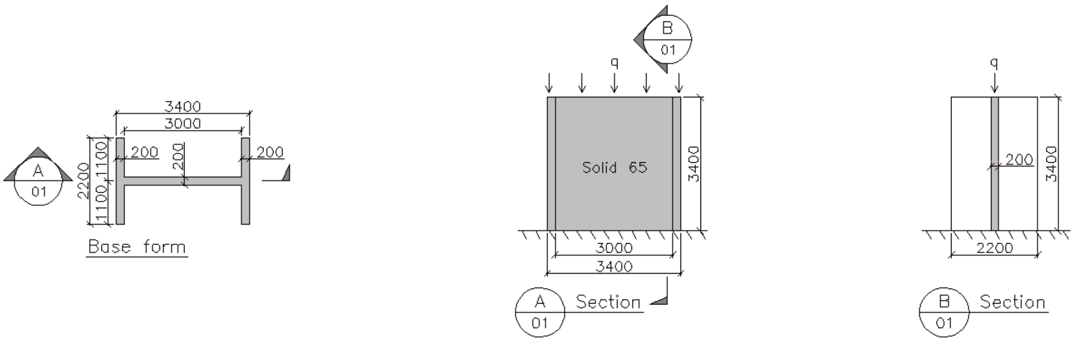


Figure 3.1. Squat wall fixed on the ground (cantilever).

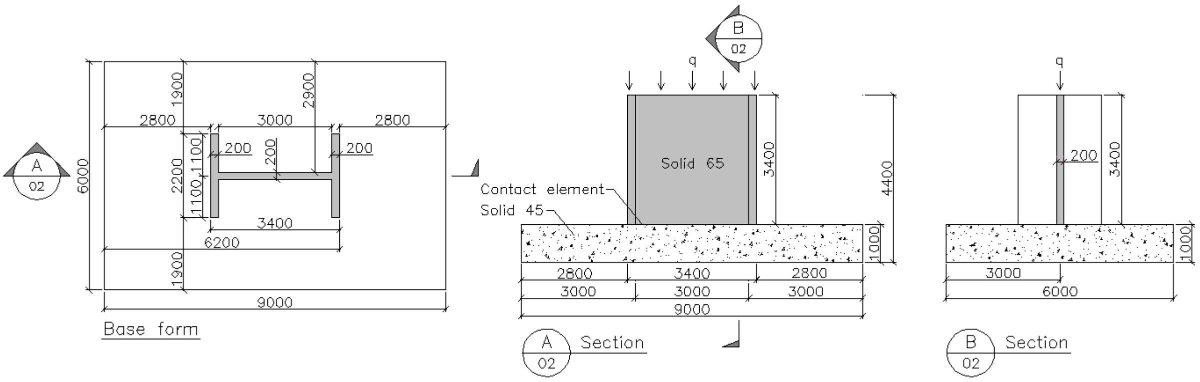


Figure 3.2. Squat walls on rock (Basalt), or on 1,0m thick mean gravel, with and without damping

The slender wall models are three times higher than the squat wall models and the distributed load q=24,5 KN/m reacts on every story. Otherwise, the slender models are similar to the squat models, i.e. in the Fig 3.3 slender wall is rigidly fixed. In the Fig 3.4 slender wall is shown contacted to rock or gravel, with and without damping.

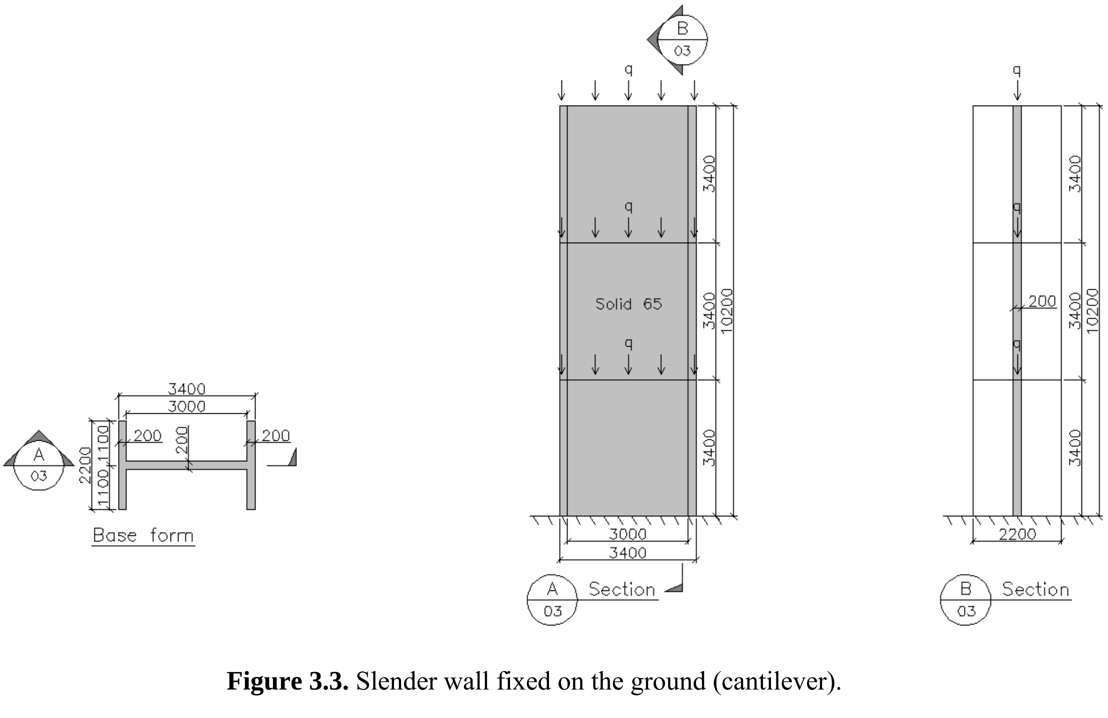


Figure 3.3. Slender wall fixed on the ground (cantilever).

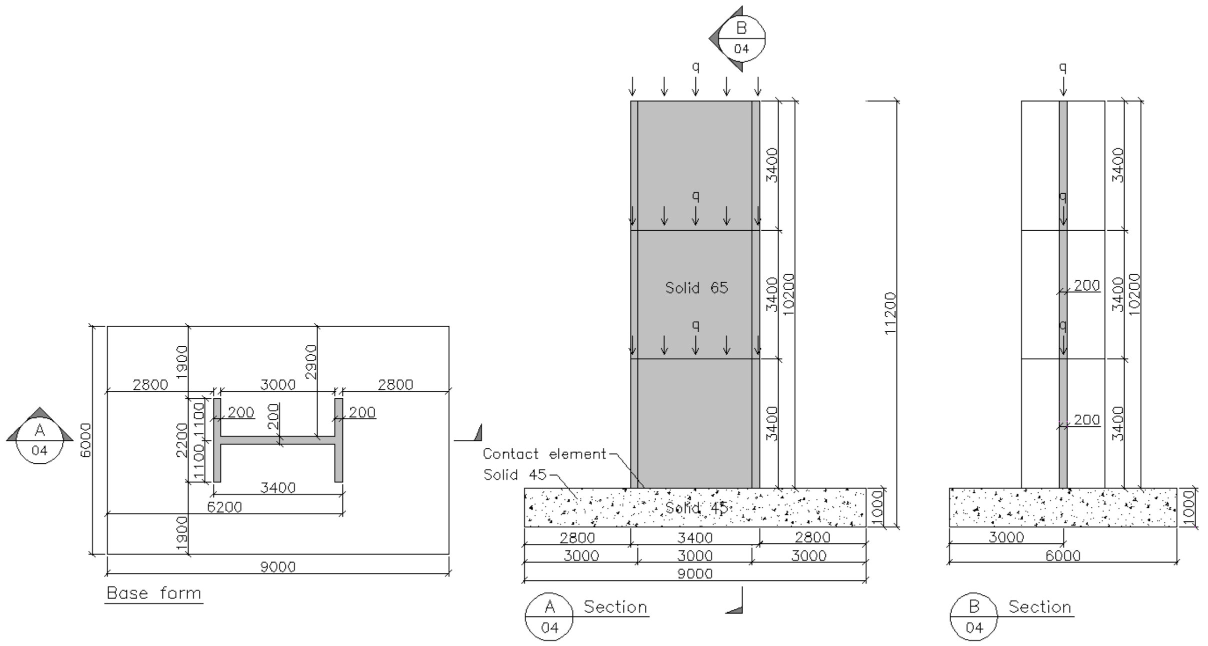


Figure 3.4. Slender walls on rock (Basalt), or on 1,0m thick mean gravel, with and without damping.

4. MATERIAL PROPERTIES

All the walls are made of concrete C25, which have compressive strength f_c = 25.0MPa and tensile strength f_t = 3.3MPa (Eurocode 2, 2004).
The reinforcement is B500, which have yield strength f_y = 500.0MPa. All the walls are reinforced in single layer in the middle of the wall in both directions with K10 c250, giving a:

$$\text{Reinforcement ratio } = \frac{A_{bar}}{A_{wall}} = 0,0015 = 0,15\%$$

The bedrock where the walls are founded on is basalt. It is appropriate because the bedrock of Iceland is mostly of basalt.
The soil where the walls are founded on is compressed mean gravel, with particle size 20 – 60 mm, cohesion 0,0 and angle of internal friction $\varphi = 40°$.
The coefficient of friction being 0.6 for the gravel isolation layer and for rock the friction being 0.7. Contact opening stiffness was chosen as no tension was allowed to form in the contact element.
More values used for the elements in these calculations are given in Table 4.1 and 4.2.

Table 4.1. Parameters for squat and slender walls and foundation.

Element	E (N/m^2)	G (N/m^2)	ρ (kg/m^3)	ν
Concrete	$25\cdot10^9$	$10.9\cdot10^9$	2400	0.15
Reinforcement	$210\cdot10^9$	$80.8\cdot10^9$	7800	0.30
Mean Gravel	$70\cdot10^6$	$25.9\cdot10^9$	2100	0.35
Rock (Basalt)	$50\cdot10^9$	$18.5\cdot10^9$	2800	0.35

Table 4.2. Parameters for foundation

Element	λ (N/m^2)	v_p (m/s)	v_s (m/s)
Mean Gravel	$60.5\cdot10^6$	231.3	111.1
Rock (Basalt)	$43.2\cdot10^9$	5353.5	2571.7

The following equations Eqn. 4.1 are applied where calculating the shear modulus and Lame parameter:

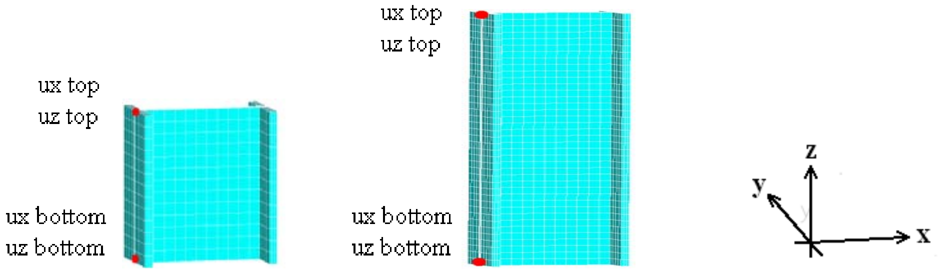
$$G = \frac{E}{2 \cdot (1+\nu)} \qquad \lambda = \frac{E \cdot \nu}{(1+\nu) \cdot (1-2 \cdot \nu)} \qquad (4.1)$$

Where, E = Modulus of elasticity.
G = Shear modulus.
ρ = Mass density.
ν = Poisson´s ratio.
λ = Lame parameter.
v_P = P-wave velocity.
v_S = Shear wave velocity.

5. ANALYSIS RESULTS

For the analytical study, a time history from Hella, South Iceland earthquake 2000 is used, (Ambraseys et al. al, 2002). Max peak acceleration reaches 0,47g. The Earthquake action is acting in the x-direction under the fixed wall, under one metre thick bedrock or under one metre thick gravel bed as shown in Fig. 3.1. to 3.4.

Two nodes are chosen; see Fig. 5-1, to monitor the nodal translation over time, one at the top and other at the bottom, to see the translation both in the x-direction and in the z-direction. Both compressive- and tensile stresses of the walls are the maximum stresses over the time history.



Squat wall Slender wall

Figure 5.1. The nodes represent where the displacements and rocking are monitored.
The coordinate system for all the walls are the same, i.e. x-direction is horizontal and z-direction is vertical.

Results from the analytical study by using ANSYS finite element program, are collected for squat walls in tables 5.1 and 5.2. For the slender walls, the results are collected in tables 5.3. and 5.4.

Five cases are shown;

1.Walls perfectly fixed to the ground.
2. Walls grounded on bedrock and allowed to rock with near-field effects.
3. Walls grounded on bedrock and allowed to rock with near- and far-field effects (damped),
4. Walls grounded on gravel and allowed to rock with near-field effects.
5. Walls grounded on gravel and allowed to rock with near- and far-field effects (damped),

Table 5.1. List of maximum displacement for squat walls. Negative value in z-direction means down direction and positive value means up direction.

Squat wall models	Displacement, x-direction		Displacement, z-direction	
	Top (mm)	Bottom (mm)	Top (mm)	Bottom (mm)
Fixed	24.246	24.280	-0.056	0.000
Bedrock	24.290	24.295	-0.487	-0.162
Bedrock damped	24.291	24.295	0.003	-0.032
Gravel	25.090	25.123	-1.911	-1.899
Gravel damped	25.604	25.389	-0.882	-1.034

Table 5.2. List of maximum stresses for squat walls. Negative value is compression stress and positive value is tension stress. Also in last column are list of maximum total shear-forces.

Squat wall models	Comp. stress x-direction (MPa)	Tens. stress x-direction (MPa)	Comp. stress z-direction (MPa)	Tens. stress z-direction (MPa)	Shear force x-direction (KN)
Fixed	-0.252	0.177	-1.727	1.289	242
Bedrock	-0.165	0.144	-1.298	0.269	185
Bedrock damped	-0.165	0.132	-1.263	0.276	171
Gravel	-0.062	0.112	-0.556	0.122	117
Gravel damped	-0.045	0.121	-0.488	0.084	103

Table 5.3. List of maximum displacement for slender walls. Negative value in z-direction means down direction and positive value means up direction.

Slender wall models	Displacement, x-direction Top (mm)	Displacement, x-direction Bottom (mm)	Displacement, z-direction Top (mm)	Displacement, z-direction Bottom (mm)
Fixed	23.983	24.280	0.205	0.000
Bedrock	37.585	24.333	6.337	6.363
Bedrock damped	57.898	24.290	17.716	17.836
Gravel	103.416	24.693	28.623	29.144
Gravel damped	133.449	24.507	31.911	32.689

Table 5.4. List of maximum stresses for slender walls. Negative value is compression stress and positive value is tension stress. Also in last column are list of maximum total shear-forces.

Slender wall models	Comp. stress x-direction (MPa)	Tens. stress x-direction (MPa)	Comp. stress z-direction (MPa)	Tens. stress z-direction (MPa)	Shear force, x-direction (KN)
Fixed	-0.550	0.438	-3.440	2.790	782
Bedrock	-0.305	0.246	-2.515	0.707	638
Bedrock damped	-0.338	0.255	-1.794	0.641	568
Gravel	-0.221	0.065	-0.877	0.538	402
Gravel damped	-0.224	0.048	-0.878	0.542	394

6. DISCUSSION

These results are in accordance with what has been previously stated, the effects of rocking of the walls change its behaviour profoundly, and displacements increased while the stresses and shear forces diminished.

For squat wall the displacements in the x-direction are same for all cases, but for the z-direction the result shown that wall are rocking on gravel bed. The compression stress and tension stress are smallest for wall grounded on gravel and the shear force is only 40% for wall grounded on gravel versus fix base scenario.

For slender wall the displacements from rocking are much bigger than from the squat wall model for bedrock and gravel as can be shown in table 5.3. The stresses also decrease from fixed base as the wall is grounded on bedrock or gravel. Furthermore, as had been shown for squat wall the shear force decrease as the wall is grounded on gravel bed.

According to these results, it had been carefully estimated that 25% less reinforcement is needed for wall on bedrock allowed to rock versus fixed wall and 50% less reinforcement needed for wall grounded on gravel versus fixed wall.

Analysis software used to design structures, using usually finite element method is quite complicated. Including the computer program ANSYS, which has been used in the analysis of this project.

Non-linear calculations by ANSYS are well known, but it shall have in mind that using the non-linear model like done here in this research is quit complicated, and results could heavily be influenced by various coefficients included in the program.

Further research is planned to confirm the results of this project. More numerical examples are going to be tested and be analysed for different soil types and foundation conditions. Further one continuance on this project will be recasting concrete walls on a laboratory and test them on a shake table. That is one of the reasons why the walls look like this in the project, because to have this possibility to put them on a shake table and possible to have a comparison with the reality walls and foundations versus model walls and foundations.

AKCNOWLEDGEMENT

The authors would like to thank Indridi Rikhardsson at Reykjavik University for great help in modulate the research cases in ANSYS program. Furthermore, the authors would like to thank Einar Helgason from Almenna Consulting Engineers for soil-structure interaction studies.

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