Seismic response of multianchored retaining walls

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Introduction

This paper examines the behavior of flexible anchored retaining wall subject to seismic action.

Flexible anchored retaining walls are often used for bridge abutments, slope-stabilization projects and retaining structures and to resist up-lift forces. They offer in many cases technically better and more economical solution for temporary and permanent structures. An advantage of soil anchors compared with other foundation methods, that the capacity of most anchors is checked after installation. The interaction between soil anchors, the retaining structure and the soil can be complex and is influenced by many factors. The load distribution behind a retaining structure depends on the method of excavation and the resulting of deflections of the wall. Secondary factors such as construction activities, static and dynamic loads, variations of the ground water level can affect the performance of soil anchors.

In regions that experience strong ground motions due to earthquakes, anchored walls often suffer severe damage and sometimes total failure. This damage demonstrates the need for seismic design procedures for tiedback walls when used as permanent structures in earthquake regions.

The placement of anchorages on a wall has de advantage of allowing the space inside the excavation will be completely available. The anchorages are usually carried out as the excavation takes place through holes containing within it a structural element that resists the forces of traction.

Actually anchorages in the soil are carried out in various countries, mainly in large urban areas with loads that generally do not exceed 1500kN.

The program used to simulate the behavior of the structure was Plaxis. This is a finite element program for geotechnical applications in which soil models are used to simulate the soil behavior. With this program is possible to obtain the forces in the structure and the tensions on the soil.

Components of a multianchored wall

The main components of a typical retaining wall are illustrated in Figure 1. The structure consists in wall facing, anchors, tendons and an anchor head that provides the connection of the tendon to the wall facing. The anchor transmits a tensile force from the main structure through the anchor tendons to the surrounding ground. The shear strength of the ground is used to resist the tensile force.

The anchors are composed of a fixed length that is bonded to the grout bulb and an unbounded free length that transfers the lateral earth forces from the wall to the anchorage zone. Anchor tendons are usually constructed of prestressed steel in the form of threaded bars or multistrand cables.

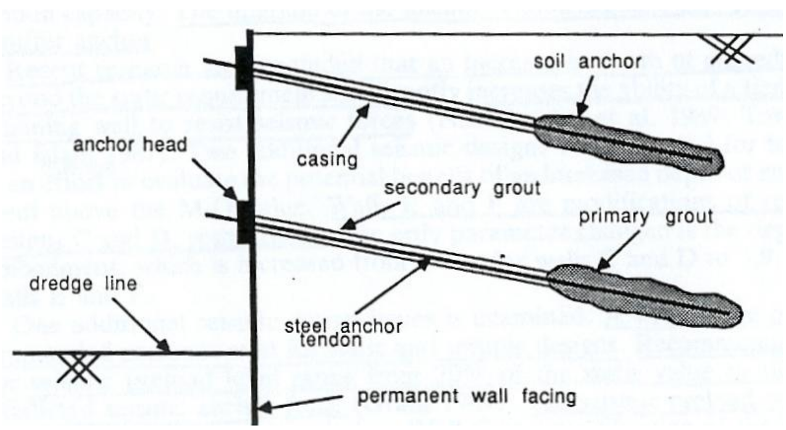

Figure 1: Components of a tiedback retaining wall. Adapted: Siller and Dolly, 1992.

Anchored walls constructed of sheet piles are usually considered flexible because of their ability to deform under the stresses they are designed to withstand. The deformation is such that they have a substantial influence on magnitude and distribution of earth pressures. Increased wall flexibility and greater distances between anchors result in increased wall movements. Therefore, earth pressure magnitude and distribution can be significantly influenced by the combined effects of wall flexibility and anchor spacing.

No standard procedure exists for the design of flexible retaining wall. Most design procedures are empirically based, because of the complex interaction between anchor preloads, the flexible wall facing and the changing soil stress states as construction proceeds.

Flexible retaining wall are structures where deformations induced by the pressures of soil produce a significant effect on the distribution of these pressures, as well as the value of impulses, bending moments and shear forces that are scaled to.

A particular aspect of flexible structures is that the bending moments are smaller than a rigid structure, when they are acted to the same actions. This is because of the pressures imposed by soil are free to redistribute in a structure more flexible. This is beneficial for flexible structures however the displacements of the wall and soil are higher. Thus, there is a compromise between the reduction of bending moments and the increases in displacement with the flexibility of the wall.

Hanna and Kurdi (1974) in Siller and Frawley (1990), investigated the influence of wall flexibility and found that walls supported by inclined anchors experienced a reduction in bending moment, however, this influence decreases with increases in wall flexibility.

Plant (1972) in Siller and Frawley (1990) reported that the wall and soil movements are magnified with increased of anchor inclination.

In problems with multi-anchored wall, the basic hypothesis is that the horizontal forces generated by pressures of soil must be balanced by the anchorages, while the relief of the vertical normal tensions caused by the hollowing it is not. In this way, the values of the induced shear stresses for the hollowing process increase significantly with the depth of excavation.

For these structures, the determination of the earth pressures and the corresponding forces in the wall and the diverse levels of anchorages is very complex, due to interaction, in each cycle of deepening of the hollowing and the new anchorage to carry through between the soil-wall-hollowing-anchorage and deformations associates.

The association of anchorages to the retaining walls allows that the wall, in service, resists the bending moments that would generate tensile unaffordable in certain sections of the wall if the prestress had not been applied.

In an anchored flexible structure, arcs are developed in vertical and horizontal planes. This effect of arc reduces the pressure in the zones most deformable and concentrates forces in the points less deformable (dues to the anchorage), redistributing the loads. These tensions are going to redistribute, however they depend of the strain by bending of the wall, the conditions of support of the wall (position and rigidity of the anchorages, values of prestress installed) and the state of the initial tension in the wall.

Static analysis of the behavior of multianchored wall

In this study the wall has 0,4m of thickness, 12m of length and the excavation has 8m of depth. The soil has 60000MPa of modulus of elasticity.

The anchorages have different lengths, the first has 15m and the second has 12m however both have a bulb with 6m and are inclined at 25º to the horizontal. They will be prestressed to 110kN/m, and are spaced of 3m.

The magnitude of deflection of the wall and the pattern of ground surface settlement were studied and compared.

Typical profiles of wall and ground movements of multianchored wall are shown in Figure 2.

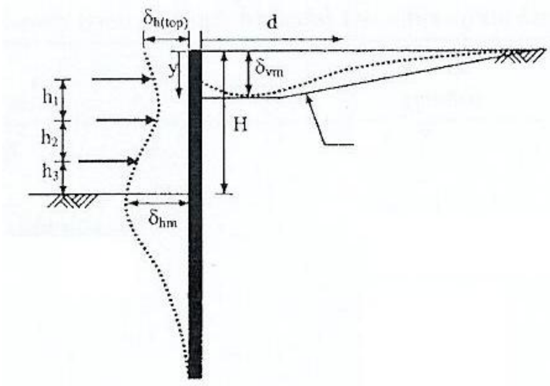

Figure 2: Typical profiles of wall and ground movement for anchored wall. Adapted: Leung et al, 2007.

In excavations with no lateral support the wall deforms as a cantilever and the resulting distribution of ground settlement is triangular. As excavation proceeds, the upper part of the wall is restrained and the wall deforms inward near the excavation level. The combination of the cantilever and deep inward movement patterns results in the cumulative movement pattern. The distribution of ground settlement is triangular if cantilever wall movement predominates, while it is trapezoidal if deep inward wall movement predominates.

In the construction of structure, there are 6 construction stages:

- Phase 1: placing the wall;
- Phase 2: excavation of the first level (3m);
- Phase 3: placing the first anchorage and prestress (110kN/m);
- Phase 4: excavation of the second level (3m);
- Phase 5: placing the second anchorage and presstress (110kN/m);
- Phase 6: excavation of the third level (2m).

For the base case, the displacement at the top of the wall for each excavation stage is shown in Figure 3. The wall tends to move inside this, and when places an anchor the wall as a tendency to reverse the movement. When placing the first anchorage and apply the prestress, it cancel the displacement at the top of the structure and moves it for the active zone of the structure. It can be concluded in a first analysis, that prestress effort can limit the displacement suffered by the structure in the later stages of construction. Thus it is clear the ability of anchorages to recover a significant portion of displacements. The displacement at the base of the structure increases as the excavation proceeds. The prestress doesn't have any influence in the maximum displacement, and does not modify to much the displacements suffered by the wall below the level of excavation.

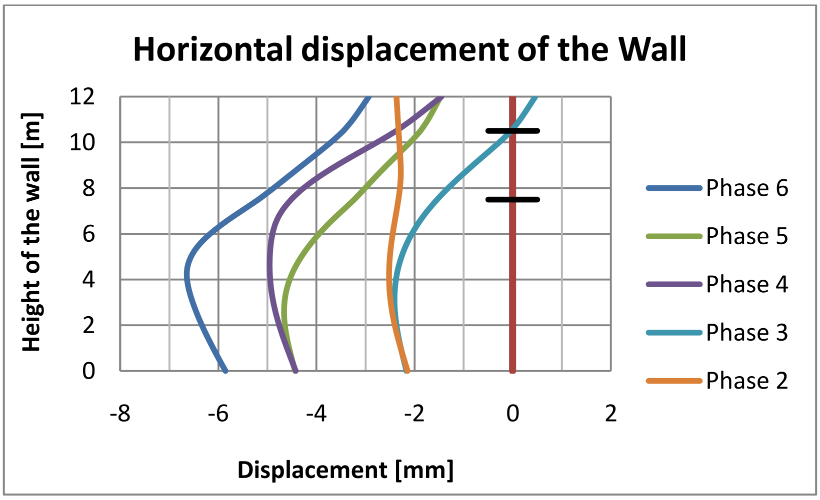

Figure 3: Horizontal displacement of the wall.

The displacement in the base should be very small, because the wall should have a tendency to "inset" in the soil. This doesn't happen possibly due the small height of the wall.

Studies by Siller and Dolly (1992) in a flexible structure with two anchorages show that the biggest displacements occur in areas where doesn't exist any anchorages and that the anchorage of second level serves to limit the displacements below the line of excavation.

In this study, that findings are verified, therefore the maximum displacement occurs at 4,5m of height and it is 6,64mm (Phase 6). When places the anchor of the second level that severely restricts the displacement between the point where it is applied and the base of the excavation.

The settlements behind the wall are shown in Figure 4.

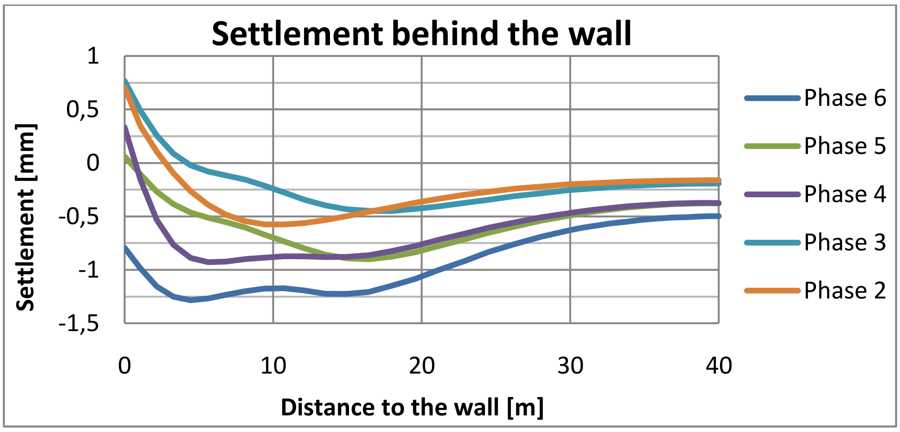

Figure 4: Settlement behind the wall.

The maximum settlement behind the wall occurs in Phase 6 at 4,5m from the wall and it is 1,28mm. From this point the settlement tends to decline and 40m of the wall has a value of 0,50mm. Note that the final settlement doesn't depend the prestress, because Phase 3 matches do 2 and Phase 5 matches do 4. The placement of anchorage limits the settlements near the wall up to 15m this. This trend is consistent with what happens with this type of structures, as shown previously.

The bending moments of the wall are shown in Figure 5. The maximum moment occurs for Phase 6 at 5,25m of height and corresponds to 52,91kNm/m. At this stage, in the zone of the first anchorage, the bending moment has a value of 41,94kNm/m and at the second anchorage is 26,99kNm/m.

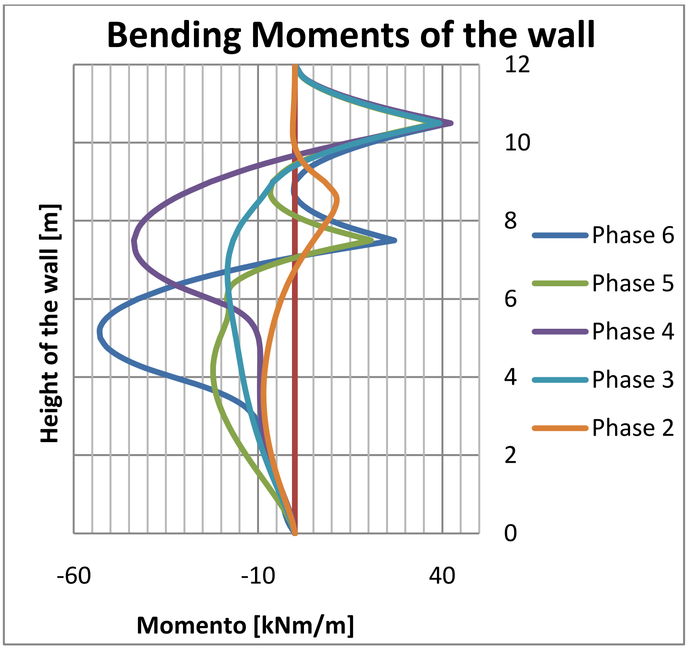

Figure 5: Bending moments of the wall.

The axial loads in anchors are shown in Table 1 and 2. This loads increase during the excavation and decrease when a lower level is prestressed.

N [kN/m]	Free Length	Begining of the Bulb	End of the Bulb
Phase 3	*110*	*94,5*	*6,7*
Phase 4	*124,7*	*112,5*	*8,4*
Phase 5	*109,5*	*97*	*7,4*
Phase 6	*112,5*	*102,4*	*9*

Table 1: Axial loads for the first anchor.

N [kN/m]	Free Length	Begining of the Bulb	End of the Bulb
Phase 5	*110*	*96*	*7,3*
Phase 6	*124,4*	*113,2*	*10,4*

Table 2: Axial loads for the second anchor.

The maximum load in each anchor occurs during the excavation following its installation. This increase is the order of 13% in both anchorages and it's a significant value. The loads in the final stage are higher than those originally installed.

For the two bulbs, the axial load must be zero at the end of them. This doesn't happen due to the high displacement that they suffer and then, the bulb debonding the soil. In this way there will occur the rupture of the soil in the end of the bulb and therefore cannot be transferred all load.

There are several factors that can influence the behavior of a multianchored structure. Thus, changes to make in this study are:

- Anchoring the first level to 17m and the second to level to 14m (the bulb has 6m in both);
- Anchoring the first level to 21m and the second to level to 18m (the bulb has 6m in both)
- Increase the length of the bulb to 9m;
- Increase of the wall thickness to 0,6m;
- Increase of the wall thickness to 1m;
- Increase in modulus of deformability of soil to E=180000MPa;
- Increase the length of wall to 16m (the excavation has 8m).

The horizontal displacements of the last constructive phase of the structure are shown in Figure 6. Note that the feature that most influences the displacement of the wall is the modulus of deformability of soil, because that is the situation that conduct the smaller displacements. It means that it is most important obtain a realistic modulus of elasticity, because it can changes all the behavior of the structure.

The progress of diagrams is very similar in most cases, except when it increases the length of the wall and when the thickness of wall is 1m.

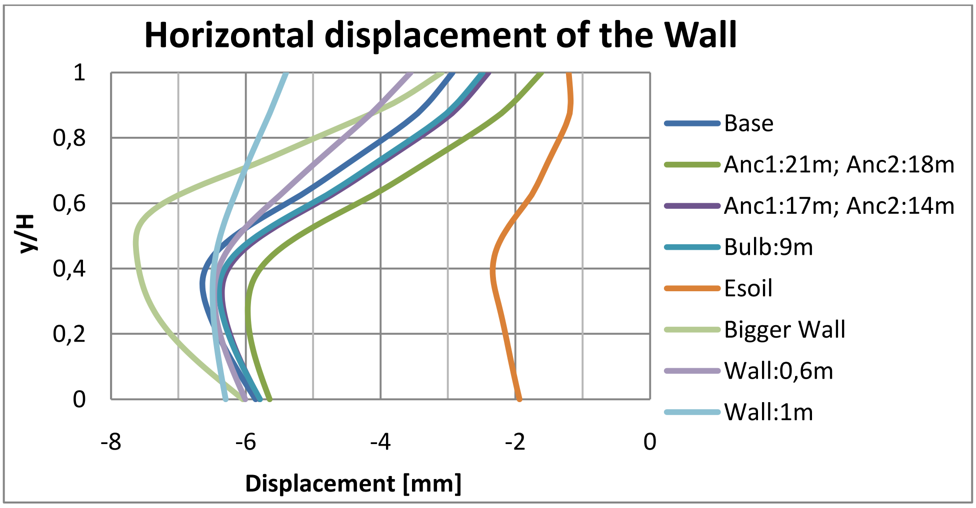

Figure 6: Horizontal displacement of wall.

The settlements behind the wall are shown in Figure 7. Once again note that is the modulus of deformability of soil that has greater importance in the settlements of the soil. It's visible that when the thickness of wall increases, the settlement near the wall increases. Be noted that the settlement of the 40m of the wall is identical to most of the parameters studied, except when increase the modulus of deformability of the soil and the length of the wall.

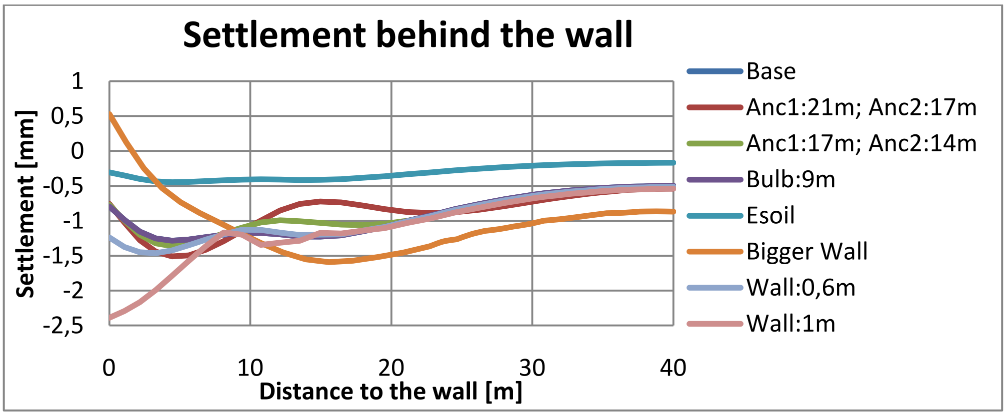

Figure 7: Settlement behind the wall.

The bending moments are shown in Figure 8. The parameter that has more importance in the value of bending moment is the thickness of wall, because it is what causes higher values.

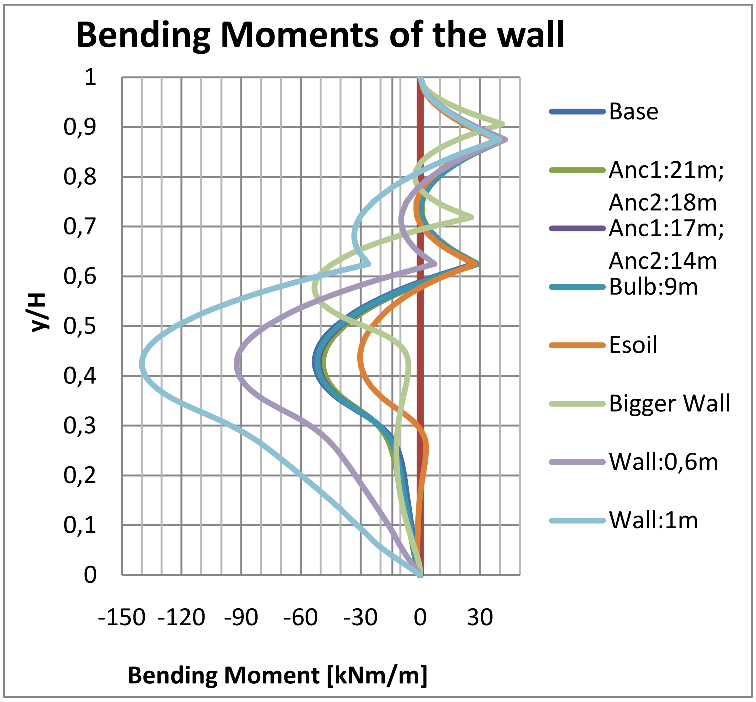

Figure 8: Bending moment of the wall.

The axial loads in both anchorages are shown in Table 3. This load in the last phase of the structure isn't very influenced by the studied parameters.

In the bulb there are small differences, due to mechanisms of progressive debonding. For example, for the case where increased the length of anchorage, the bulb doesn't transmit 20kN/m for the ground, which means a significant value comparing with the base case. This particularity of the bulb and its incapacity to transfer all the loads to the soil raises the possibility of the solution are not equilibrated. In reality, what happens is that the equilibrium of forces has to be understood in global way, that is, the deformation of the supported soil contributes for generated forces that we cannot observe in the results, but they contribute to the equilibrium.

	Axial Load (kN/m)					
	1ª Anc.	*Begining of Bulb*	*End of Bulb*	*2ª Anc.*	*Begining of Bulb*	*End of Bulb*
Base Case	*112,5*	*102,4*	*9*	*124,4*	*113,2*	*10,4*
Anchor Length: 17m+14m	*112,9*	*105*	*11,6*	*123,7*	*112,6*	*12,9*
Anchor Length: 21m+18m	*114,1*	*106,5*	*12,4*	*122,5*	*111,2*	*20*
Bulb: 9m	*113,1*	*105,1*	*10,9*	*125,4*	*116,5*	*9,9*
Bulb: 12m	*113,6*	*106,2*	*10,7*	*126*	*117,5*	*14,8*
Wall: 0,6m of thickness	*114,9*	*105,1*	*9,4*	*124,4*	*113,3*	*10,6*
Wall: 1m of thickness	*120,1*	*111,3*	*10,2*	*123,3*	*112,9*	*10,9*
E_{soil} = 180000 MPa	*111,7*	*100,2*	*8,6*	*116,6*	*104,2*	*9,6*
Increase in wall Length (16m)	*114,2*	*103,3*	*10*	*127,3*	*114,2*	*10,1*

Table 3: Axial loads in both anchorages.

Dynamic analysis of the behavior of the wall

Dynamic loads are imposed on soils and earth structures by several sources, such as earthquakes, bombs, operation of machinery, construction operations, traffic, and wave actions.

For dynamic analysis of retaining structures, the earthquakes are an important dynamic load source on ground. That is because the potential damages that an earthquake can provoke and this fact represents an uncontrolled and unexpected phenomenon of nature.

In accordance with FHWA, 10 observation of seismic performance of anchored walls have been made when California earthquake of 1987 occurred. Those observations indicate overall good performance of anchored walls systems. Only one of ten anchored walls was design to withstand seismic forces and all walls examined performed very well and experienced little to no loss of integrity due to the earthquake. The same conclusion was drawn following a survey of the performance of anchored walls conducted following the 1994 Northridge earthquake.

The stress-strain properties of a soil and its behavior depend upon several factors and can be different in many ways under dynamic loading conditions as compared to the case of static loading.

The earthquake considered in this study is the Upland earthquake of 28 of February of 1990, characterized for a peak acceleration of 239,874cm/s^2, which means 25% of the gravity acceleration.

The acceleration reached in the top and base of the structure is shown in Figure 9.

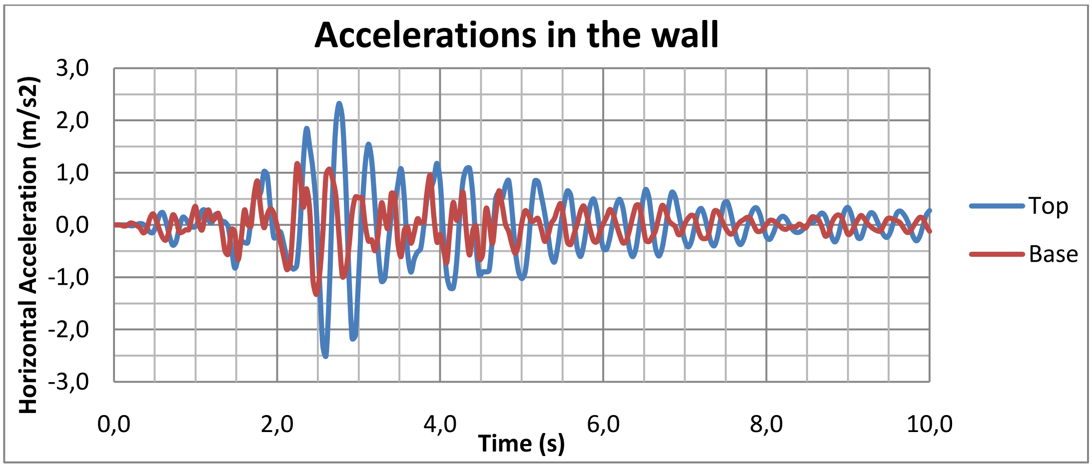

Figure 9: Accelerations in the wall.

It is visible that the acceleration increased the base for the top. The maximum acceleration in the top of the structure is a very significant value of 0,255g, and in the base is 0,136g, where g is the gravity acceleration.

It can be visible in Figure 10, that the final displacements (at 10s) doesn't coincide with the maximum displacements suffered by the wall, because when the earthquake occurs, the wall initially has negative displacements and when the acceleration increases, the wall trend to dislocate inside the soil, acquiring positive displacements, with the maximum value of 36mm, decreasing with the reduction of acceleration. The final displacements of the wall are shown in Figure 11.

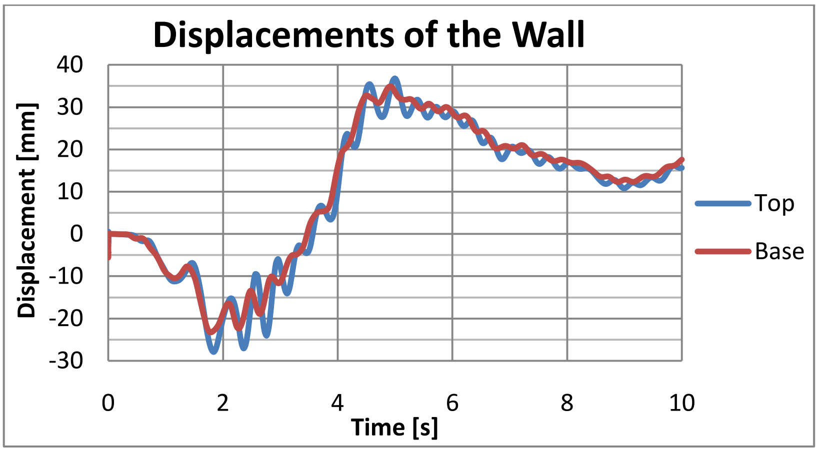

Figure 10: Displacements in the wall when an earthquake occurs.

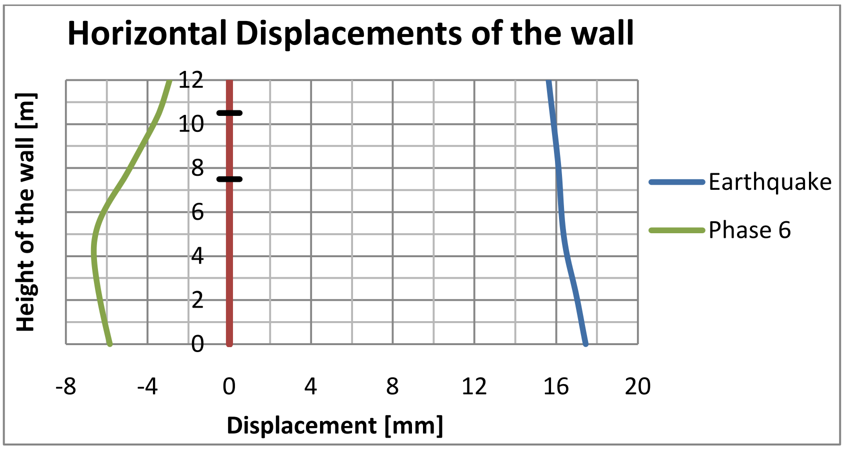

Figure 11: Horizontal displacements of the wall in Phase 6 and at the end of earthquake.

In Figure 12 are shown the settlements behind the wall. As de wall moves inside the soil, it is normal that the soil has a displacement to the top near the wall. The maximum displacement is 1,3mm and occurs about 9,4m behind de wall.

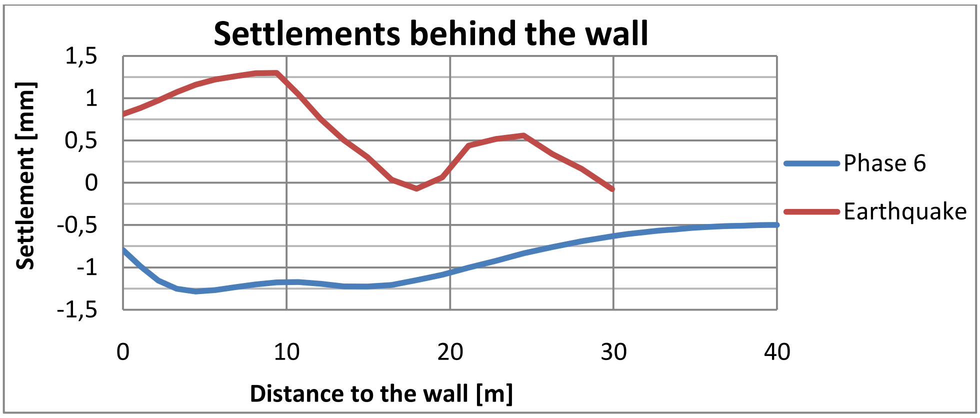

Figure 12: Settlements behind the wall.

Involving of bending moments is presented in Figure 13. The moment in the zone of the first anchorage doesn't have alteration when the earthquake occurs. However, the bending moment in the second anchorage and the maximum have bigger values. In the second anchorage the value is 38,0kNm/m and the maximum is 75,9kNm/m, while in phase 6 these values were 27,0kNm/m and 52,9kNm/m, respectively.

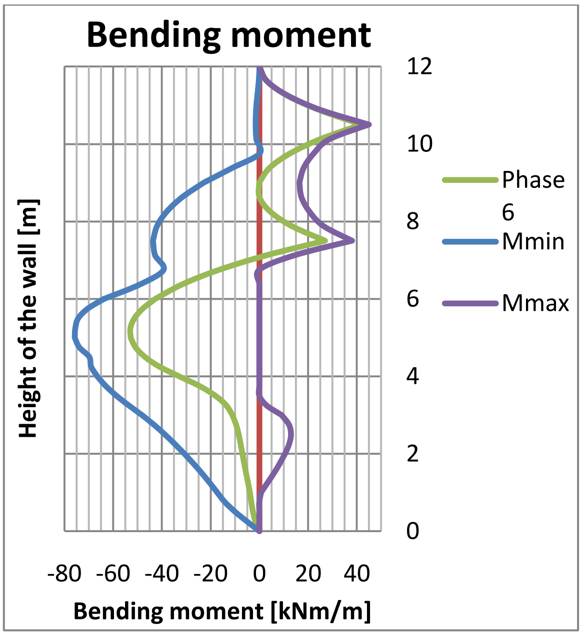

Figure 13: Involving of bending moments.

The horizontal stress when the earthquake occurs is show in Figure 14. The average of the horizontal stresses is 32,8kPa, meaning a relatively small increase comparing to phase 6 (31,5kPa).

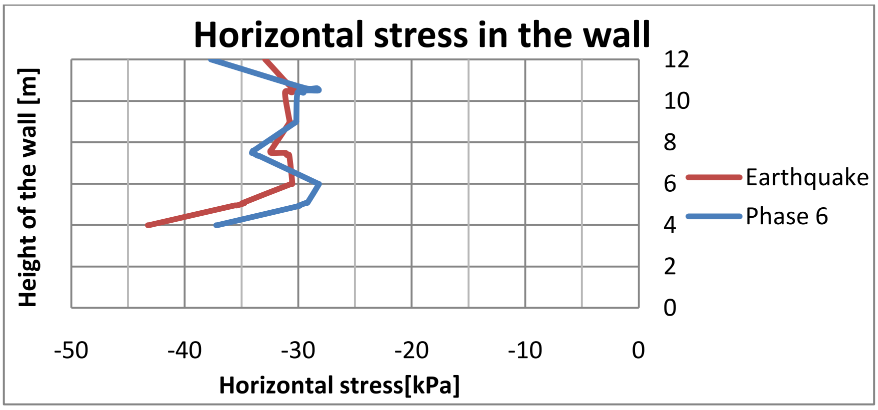

Figure 14: Horizontal stress in the wall.

In accordance with the Mononobe-Okabe method, is possible to calculate the mean stress behind the wall.

γ (kN/m³)	*18*
H (m)	*8*
Φ (º)	*35*
δ (º)	*17,5*
i (º)	*0*
β (º)	*0*
k_h	*0,1825*
k_v	*0*
θ (º)	*10,3*

$$P_{AE} = {}^{1}/_{2}\, K_{AE} \times \gamma \times H^2 = 210{,}52\ kM/m$$

$$K_{AE} = \frac{cos^2(\emptyset - \theta)}{cos\theta \times \cos(\delta + \theta)\, D} = 0{,}365$$

$$D = \left[1 + \left(\frac{sen(\emptyset + \delta) \times sen(\emptyset - \theta)}{\cos(\delta + \theta)}\right)^{1/2}\right]^2 = 2{,}6$$

$$\sigma_{média} = \frac{210{,}52}{8} = 26{,}3\ kPa$$

The horizontal stress calculated with this method has a difference with the value gotten through the Plaxis, with a variation of -20%. This difference is significant for the behavior of the wall if only analytical calculation will be made.

The maximum axial load that are in the anchorage dues the earthquake are presented in Table 4 and 5. Comparing whit phase 6, the variation of axial load in bulb is about 32 and 34%. This value is very significant for the design of anchorages.

N [kN/m]	***Free Length***	***Begining of the Bulb***	***End of the Bulb***
Phase 6	*112,5*	*102,4*	*9*
Earthquake	-	*150,4*	*26*

Table 4: Axial load in the first anchorage.

N [kN/m]	***Free Length***	***Begining of the Bulb***	***End of the Bulb***
Phase 6	*124,4*	*113,2*	*10,4*
Earthquake	-	*171,6*	*24,9*

Table 5: Axial load in the second anchorage.

Studies made for Siller and Frawley (1992), show that when the acceleration and the stiffness of the anchorages increase, the force in the anchorage also increases.

In this work it’s concluded that the increase of the axial loads in the anchorages it’s bigger, so the stiffness and the number of anchorages, the type of the soil, or the type of the earthquake can influence this parameter greatly.

It was also observed that, when the earthquake occurs, more plastic point in the end of the bulb are generated, so it can conclude that there are a progressive debonding of the bulb that is bigger than the phase 6. Therefore, the earthquake can significantly modify the design of the anchorages, because the load at the beginning of the bulb it’s bigger, and the debonding increases when the axial load increases to.

The horizontal displacements of the bulb are very similar to the displacements of the wall then, it can be concluded that the structure have a displacement as a rigid body when the earthquake occurs.

Conclusions

The efficiency of anchorages in reducing the movements of the wall, is through prestress, to recovering part of the displacements of the wall in previous phases. On particularly is that the prestress doesn’t influence the displacement at the base of the wall.

The evolution of the loads in anchorages in all phases was analyzed. It was concluded that the maximum axial load is always in the phase following the installation of prestress, decreasing in the later stages.

The free length of the anchorage only influence the displacements at the top of the wall, and don’t have significantly influence on the other results studied, so it’s not a very important parameter in the behavior of the structure.

The flexibility of the wall is the most important parameters studied, because when it increase, the wall tends to move as a rigid body. When the wall has 1m of thickness the maximum settlement occurs at the wall.

The modulus of deformability of the soil is also the parameters with greater interest in the behavior of the structure, because when it increases, the displacements of the wall are smaller. This parameter can limit the settlements up to 40m away from the structure. The diagram of bending moments is slightly different from previous cases, because the maximum moment occurs in the level of the first anchorage, thus limiting the bending moments on the wall below the level of the second anchorage.

The increase of the wall length increases the displacement below the level of the second anchorage.

In a dynamic analysis, when an earthquake with a peak acceleration of 2,4m/s^2 occurs, several changes of the behavior of the wall are observed.

The maximum displacements in the wall it's not the same as they are settled at the end of the earthquake.

The Mononobe-Okabe method provides values lower by 20% to those obtained through the Plaxis, so it's necessary to take care when the design is based just on this analytical method.

Another significant change is the axial loads in the anchorages. This loads has an increase of 30% compared with the static case.

The bulbs of two anchorages continue to suffer a mechanism of progressive debonding, so is formed more rupture points at the end of the bulbs.

It can conclude, that the all the structure tends to move as a rigid body when an earthquake occurs, because the horizontal displacements of the wall are those suffered by the bulbs.

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