Research into the causes of the measured displacements of a quay wall

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Abstract

In this paper, an investigation into the causes of measured deformations of a quay wall in the Port of Rotterdam is described. Measurements show that horizontal displacements of the combi wall in seaward direction, increasing nonlinearly in time. This trend was the reason for an investigation into all possible causes of the horizontal displacements on top of the quay wall. The main part of the investigation was elaborated by considering the different influences for a representative cross section by simulating the real soil behaviour with analytical and numerical methods. Examples of effects that have been analysed are time dependent soil behaviour, anchor wall capacity, the influence of expected values in stead of a design philosophy, the influence of the position and magnitude of a surcharge load and accumulating effects of cyclic loading.

Keywords: quay wall, anchor wall, local surface load, cyclic loading, time-dependent soil behaviour

1 Introduction

In 2003 a quay wall was built to replace an existing wharf. A combined tubular wall was installed and some of the concrete piles were reused as foundation piles for the relieving platform. Anchorage for the quay wall was provided by an anchor wall and prestressed anchor strands. Measurements to the horizontal movement of the quay wall showed a trend with increasing deformations in time into seaward direction. This was the reason for the owner to initiate an investigation into the causes of the horizontal displacements. Therefore, the Engineering Department of Public Works of Rotterdam (PWR) facilitated a thorough research into all possible causes of the measured results, as a graduation project. The research consisted of analytical and numerical methods to simulate the real soil behaviour.

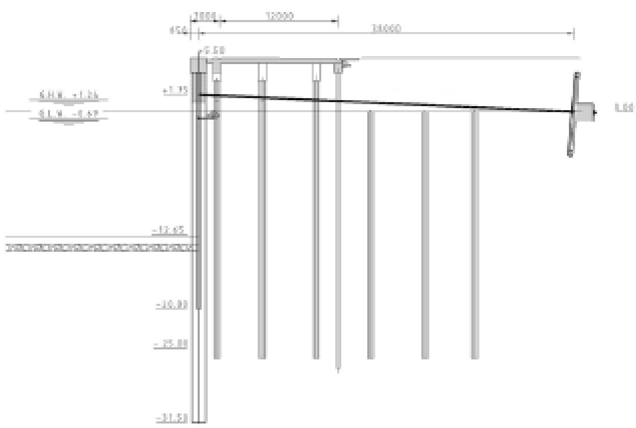

Fig. 1 Cross section of the quay wall

2 Problem description

The measurements showed deformations that are not yet stabilised after about 7 years of continuous movement, see figure 2. In combination with the complex building sequence, stratification of the subsoil and unknown really applied load cases that could have been applied, it was not possible to provide a clear explanation immediately. Furthermore, if no explanations can be given to the observations, it is not possible to give a prediction for further developments.

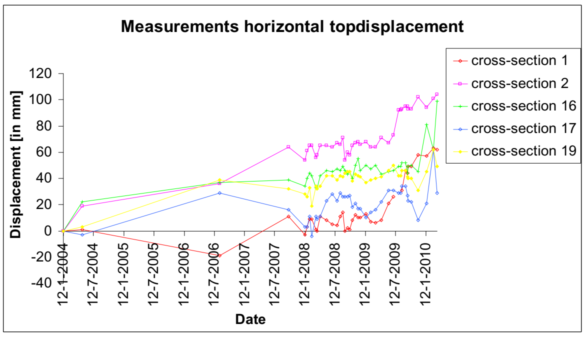

Fig. 2 Development horizontal displacement in time

3 Results

The mentioned problem was the reason to conduct a research in order to find out which possible effects could have contributed to the measured displacements.

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Time dependent soil behaviour
A first effect that is analysed as a possible cause is time dependent soil behaviour. It is imaginable that time dependent effects like consolidation and creep played an important role in establishing the increasing deformation trend in time. To provide insight into the consolidation and creep processes, many hand and FEM calculations had been made to explain that both time dependent processes counteract each other. During prestressing of the anchor strands consolidation takes place which moves the combi wall into the soil. Based on in situ tests, the present clay layers appeared to posses an anisotropic character and seemed to have a higher permeability in horizontal direction than in vertical direction. Therefore, the period in which consolidation had taken place should have been relatively short. On the other hand, creep is considered. For this effect damping out seemed to be much more time consuming. From calculations, it was concluded that within the period of the operational stage of the quay wall, the negative top displacement due to consolidation cancels out against the positive top displacement due to creep, see figure 3. Thus, time dependent soil behaviour can not be assigned as an explanation for the measured top displacements.

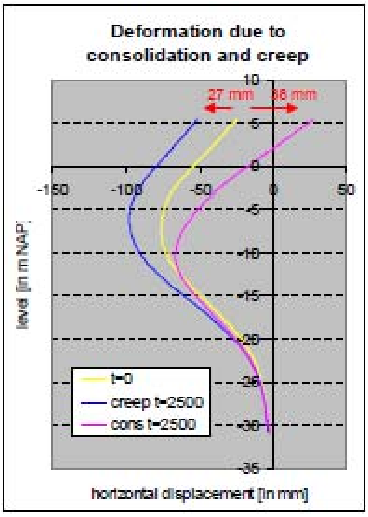

Fig. 3 Deformation in time due to consolidation and creep

Anchor wall capacity
A second effect that is investigated is the capacity of the soil in front of the anchor wall, see figure 5. Insufficient anchor capacity results in additional deformation. Due to an improved passive soil wedge over 10 metres in front of the anchor wall, it was not very likely that the soil capacity was insufficient.

Based on calculations, it was concluded that this influence was negligable in relation to the measurements.

Fig. 4 Anchor wall and reused foundation piles

A locally applied surcharge load
Thirdly, the effect of a locally applied surcharge load is investigated as a possible cause by using FEM calculations to simulate and predict top displacement of the quay wall for different imposed load cases. Later, results from calculation had been compared to the measurements. Horizontal displacements were increasing significantly with a smaller distance between the load and the anchor wall. An increasing magnitude of the load resulted in more deformations as well, especially near the anchor wall, as becomes visible in figure 6.

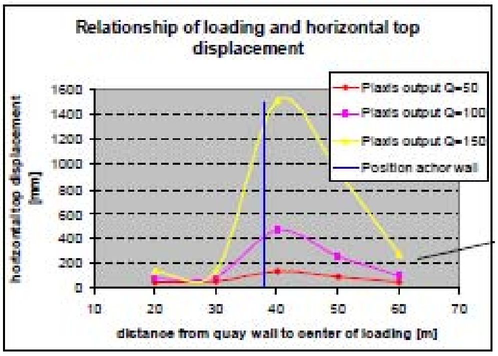

Fig. 5 Relation between position and magnitude of a locally applied surcharge load

A locally applied surcharge load can indeed be used as an explanation for the measured displacements. However, the deformation in time (still increasing horizontal displacements after 7 years of loading) is not yet clarified. Therefore, an extra time dependent mechanism is investigated: cyclic loading of the locally applied surcharge load.

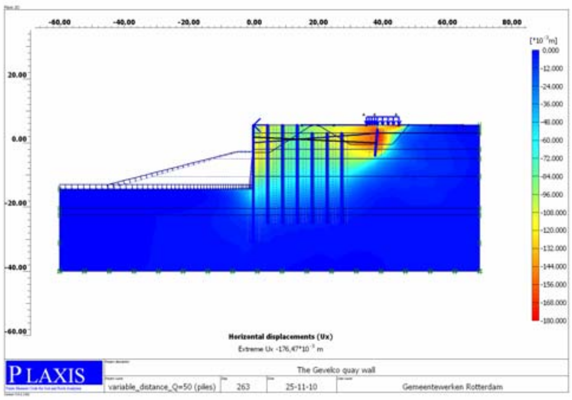

Fig. 6 Local deformation due to locally applied load

Cyclic loading: accumulation of pore pressure

Usually, variable loads are accounted for in designs with an extra partial safety factor. Accumulating effects are neglected here. In reality, it is imaginable that during cyclic loading of fully saturated soil, the continuous generation and dissipation of excess pore pressures can cause an adjustment (densification) of the grain skeleton. This phenomenon is comparable to the decrease in volume of unsaturated soil under cyclic loading. In order to approach the real soil behaviour an accurate description of the development of the excess pore pressure in time was to be obtained. However, in saturated soil the volume change is initially prevented by the water inside the pores, while in the unsaturated soil the soil body can deform freely. The grain skeleton can change from a moderate packing into a denser packing and that, due to a volume decrease, excess pore pressures can be generated because water can not flow out fast enough. The increase in stresses will initially be taken by the water present in the soil. After unloading, the excess pore pressure due to the cyclic loading (the instantaneous excess pore pressure) is vanished immediately while the excess pore pressure due to rearrangement of the grains (the residual excess pore pressure) will reduce in time. However, if the soil is reloaded shortly after the previous loading, the residual excess pore pressure is not yet completely dissipated. The excess pore pressure in the soil is now higher than just the increment due to the surcharge load. Accumulation of excess pore pressures occurs. At every following load further densification and thus accumulation of excess pore pressures is imposed. Eventually, an equilibrium (steady) state can be reached where the generation of pore pressures due to cyclic loading is balanced out with the dissipation due to consolidation. In the worst case, the excess pore pressures reach as high as the value of the initial effective stresses.

For this case, this was not an issue due to a relatively high permeability and a low freqency of 28 days between loading and unloading, see figure 7.

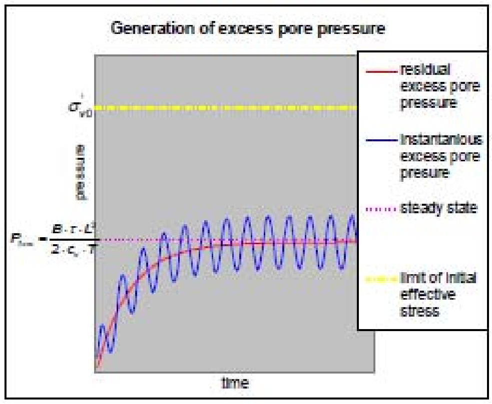

Fig. 7 excess pore pressure ‘’built up’’

Cyclic loading: accumulation of plastic strains

Although strains due to consolidation will not occur because the excess pore pressures hardly increase, strains can still accumulate under cyclic loading. When loading the active soil wedge of the anchor wall, it displaces in seaward direction. When the combi wall displaces with about the same distance, no compression of the intermediate soil body will take place. Subsequently, in the movement of the combi wall again irreversible strains will develop. This means that, at unloading, the combi wall will hardly return to its original position. The combi wall is attached to the anchor wall with anchors. Therefore, the anchor wall will neither return to its original position (the barb effect). After the second loading, displacements of the anchor wall will be less because of a higher stiffness. At reloading, stresses will be redistributed and new primary stress states will occur where new stress points have to be mobilised, resulting in new plastic strains. This process keeps repeating after every cycle and accumulation of displacements of the anchor and combi wall will occur for the load case in figure 8. The increment in horizontal displacement per cycle decreases because less redivision of stresses and less new plastic points had to be mobilised, this is shown in figure 9. In reality, it will take some time before the combi wall deforms after a displacement of the anchor wall. Therefore, the here described mechanism holds for loads with a low frequency. It is assumed that 28 days of loading is sufficient for the combi wall to re-set to a new position. For this phenomenon, a period of loading and unloading of 56 days is assumed again to be frequently occurring.

In Plaxis, 46 subsequent cycles are analysed in a consolidation analysis. From the previous part, it was proven that consolidation-related strains will hardly occur but since it is difficult to determine whether the soil behaviour is drained or undrained in the period of loading and unloading, 46 cycles, almost 7 years of continuous loading and unloading, is suggested to be sufficient to show a trend. This is the period between the first operational loading of the quay wall and the present. In this paragraph, the influence of cyclic loading with a certain period is investigated. In this period, consolidation takes place, as it does in reality. Apparently, a certain accumulation of displacements occurs.

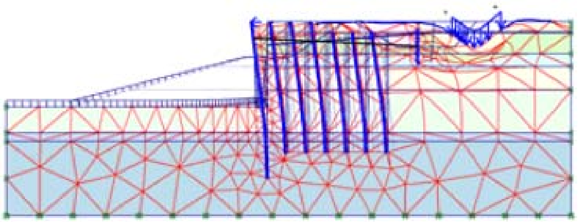

Fig. 8 Position local load

An accumulation of 210 mm developed over a period of 7 years for a load case of a locally applied load of 150 kN/m2. For different load cases the accumulation was 113 or 47 mm for a load of 100 or 50 kN/m2, respectively. Results are plotted in figure 9. Apparently, the relationship between the magnitude of loading and additional deformations due to accumulation is not linear. The higher the load, the more new plastic points are being mobilised and thus the more redivision of stresses will occur. This can also be observed in figure 9. In the material models manual of Plaxis it is stated that accumulation of irreversible strains under cyclic loading is not incorporated. If one considers a specific point in the geometry only affected by cyclic loading this is true. The soil behaviour in an unloading-reloading cycle of the stress-strain diagram of the HSsmall model is supposed to be fully elastic. So, if Plaxis does not account for accumulation of plastic strains, another explanation has to be found for the accumulation in figure 9. Consider a point near the anchor wall. At loading, the strain increases while the anchor force decreases initially. With a certain delay the anchor force will increase again while the combi wall moves in seaward direction. At unloading the soil will only return partially due to plasticity. After every next loading, new stress states are being created resulting in additional strains, accumulating in time. This explains the observed accumulation of the graph in figure 9.

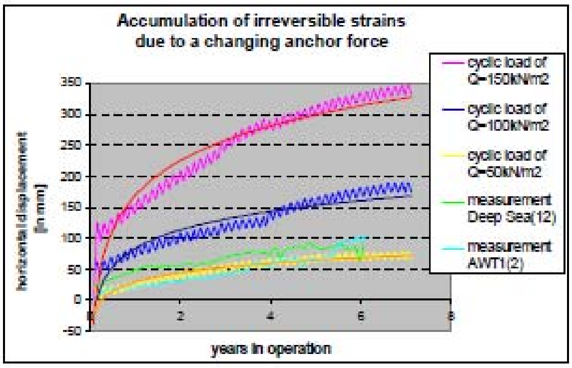

Fig. 9 Development of displacement in time

4 Recommendations and conclusions

Numerous possible combinations can be made with the above given causes which all result in the measured displacements, individually. Although the exact combination that caused the 100 mm top displacement can never be appointed, all separate causes have now been revealed and insight into the (failure) mechanisms has been provided, qualitatively and quantitatively. If the measurements are being reconsidered, it can be said from the graph of the measurements that displacements were seemingly increasing in time. If these lines were extrapolated in the future, large deformations would show up. Calculations showed that the only time effect that could play a significant role in the seven years of operation is accumulation of strains under cyclic loading. The increments in displacement would show a logarithmic trend if the magnitude of the load was constant. In reality, cyclic loading took place but the load was never constant. Due to a changing load magnitude and position, accumulation did not came true as a clear logarithmic development in time. At instants of higher surcharge loads or loading in the close environment of the anchor wall, the increment of the measured displacements were larger. This explains the irregular but mainly increasing horizontal measured displacements in time. A combination of the magnitude of loading, position of loading and the type of loading (cyclically) eventually resulted in the measured displacements.

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