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Numerical analysis of the backfilling sequence effect on gravity retaining wall behaviour

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Abstract: Gravity retaining walls derive their capacity to resist lateral movement through the dead weight of the wall. The design methodologies proposed by standards do not take into account the construction sequences that simulate the process by which the soil and retaining wall are brought together. However, in reality, at least during the backfilling process, the retaining wall undergoes many displacements that are not so far considered in the design. In this investigation, effect of construction sequences in the gravity retaining walls with different shapes is investigated with the help of finite element method. Two different construction sequences, namely the backfilling after wall construction and the backfilling parallel to wall construction, are compared for different wall shape models. Lateral displacement of the bottom and the top of the wall is plotted for each model and construction sequence with construction stages. Bearing pressure distribution, lateral earth pressure and failure wedge angle are summarized and compared with design values. Each wall showed different behaviours for each of the construction sequences. Back filling after wall construction minimizes the sliding failure and bearing pressure. Overturning failure could be reduced by backfilling parallel to wall construction. However, it was observed that, comparatively, backfilling after wall construction is effective than backfilling parallel to wall construction, suggesting that proper selection of construction method also may reduce negative effects on the wall stability.

Keywords: gravity retaining wall, construction sequence, numerical modelling, backfilling, lateral displacement

1. Introduction

To ensure stability of retaining structures, they shall be designed to withstand lateral pressures due to soil and water, the effects of surcharge loads, self-weight of the wall, and earthquake loads. In addition, earth-retaining systems shall be designed to provide adequate structural capacity with acceptable movements, adequate foundation capacity with acceptable settlements, and acceptable overall stability of slopes adjacent to walls. These are the serviceability requirements. The tolerable levels of lateral and vertical deformations are controlled by type and location of wall structure and surrounding facilities.
Gravity retaining walls derive their capacity to resist lateral loads through the dead weight of the wall. The gravity retaining wall types include rigid gravity walls, mechanically stabilized earth (MSE) walls, and prefabricated modular gravity walls.

In the construction process of retaining walls, back fill is done after the construction. This is the traditional method we usually use. However, often construction sequence is not taken in to account in the design methodology of the retaining walls. In overall the stability design is believed to be reliable and accurate, because the safety factors have been allowed in design calculations. However, would the design calculations be adequate against the disturbances during the construction sequence? Would different construction sequences determine the stability of gravity retaining walls? With respect to construction sequence, which is the most suitable shape for gravity retaining wall? These are the main questions that would be addressed in this research.
Research on influence of compaction behind the retaining walls were carried out by Broms (1971), Transport and Road Laboratory-UK (1977, 1980, 1989), Ducan and See (1986), and Kulathilaka (1990). Ahmed (2012) explored the effect of construction sequences on the behaviour of a backfilled retaining wall. In his investigation, the influence of the construction sequences on the behaviour of an L shaped stiff retaining wall was investigated with a numerical model. He had

obtained the same observations and results by the experimental tests as well. These observations highlighted the fact that rotations and translations of the wall occur simultaneously during the staged backfilling process, which better simulate the real construction process.
However, the design methodology does not take into account the construction sequences that simulate the process by which the soil and the gravity retaining wall are brought together. There is little research which addresses the effect of construction sequences of gravity type retaining walls. Possible construction sequences are backfilling after wall construction and backfilling parallel to wall construction. This research will compare both construction sequences for different shapes of gravity retaining walls.

2. Objectives

The objectives of the study were, (i) to carry out a through literature survey on the area of investigation, (ii) to carry out numerical analysis on the effects of construction sequence on different shapes of gravity retaining walls, and (iii) to investigate the effects of construction sequences on bearing pressure distribution and failure wedge of gravity retaining walls.

3. Methodology

An extensive literature review was conducted to identify the research need and to gain necessary knowledge on the topic. By preliminary calculations different shapes and the dimensions of the retaining walls were determined. A finite element analysis using PLAXIS was conducted for the two construction sequences (backfilling after wall construction and backfilling parallel to wall construction). The results were illustrated using appropriate graphs and diagrams (for bearing pressure distribution, failure surface, wall deformation shape etc). By further analysis of the results the conclusions and suggestions were made.

4. Retaining Wall Design

In order to construct the finite element model for this study, retaining walls were designed based on BS 8002 design guide. Three different shapes with constant height and cross sectional area were selected and trial method was used to get proper stable retaining wall based on BS 8002.
In the design procedure, first force exerted on the retaining wall was estimated by considering the statical equilibrium on the soil wedge bounded by the wall, the failure surface and the surface profile. Calculations were based on Coulomb's method of analyse and wedge method.
The soil properties used in design are the dry density γ_{bulk}=18 kN/m^3, the angle of shearing resistance ϕ=32^o, and the coefficient of cohesion C=0. The retaining wall was designed as mass concrete wall with concrete Grade 40 N/mm^2, young's modulus E=26MN/m^2, and density γ=24kN/m^3.
Optimal base sizes were calculated for three walls by considering overturning, sliding, and bearing capacity. Cross section area and height are maintained as constant. The dimensions were calculated considering the safety against self-weight failure.

5. Format of Reference Lists

Performance of an earth retaining system depends on many factors, in particular, successive stages of construction. The conventional design methods using design guidelines are not capable of evaluating the yield information on likely displacements in the system. The finite element analysis, which is widely used in design practices today, can be used to model complex soil-wall interaction problems.
Numerical analyse was carried out in plane strain and 15-nodes triangular elements. Movement of the wall is the major consideration in determining the wall deflection. Hence fine mesh was used in the model. Soil was modelled using Mohr-Coulomb model and concrete wall model as linear elastic model. The utilized soil modelling parameters and concrete retaining wall modelling parameters are presented in Table 1 and Table 2.

Table 1: Concrete properties

Parameters	Name	Concrete	Unit
Material model	model	Linear elastic	-
Type of material behaviour	type	Non-porous	-
concrete unit weight-Grade 40	γ_{bulk}	24	kN/m^3
Permeability in hori,vert.dirn	k_x, k_y	0	m/day
Young's modulus	E_{ref}	26,000,000	kN/m^2
Poisson's ratio	v	0.15	-
Strength reduction factor	R_{inter}	-	-

Table 2: Dense sand properties

Parameters	Name	Dense sand	Unit
Material model	model	M-C model	-
material behavior	type	drained	-
Soil unit weight	γ_{bulk}	18	kN/m^3
Permeability in hori.& vert.dirn	k_x, k_y	0.36	m/day
Young's modulus	E_{ref}	20,000	kN/m^2
Poisson's ratio	v	0.3	-
Cohesion	C_{ref}	0.1	kN/m^2
Friction angle	φ	32	°
Dilatancy angle		2	°
Strength reduction factor	R_{inter}	1	-

6. Construction Sequences

In order to investigate the effect of the construction sequences, the backfill soil was divided into 6 layers of 0.5m thick each that yield the total initial height of 3m. The general layouts of the geometry configuration of numerical model are as shown in figure 1, 2, and 3.

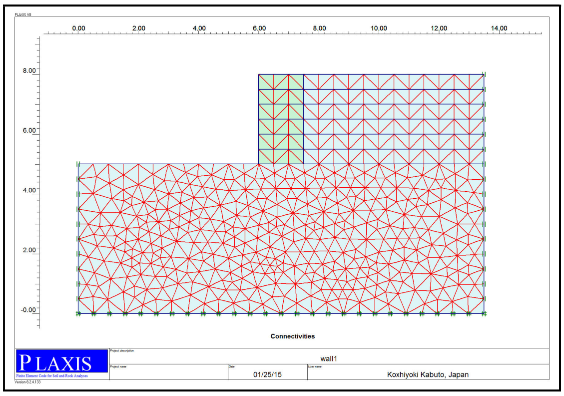


Figure 1: Finite element model-1

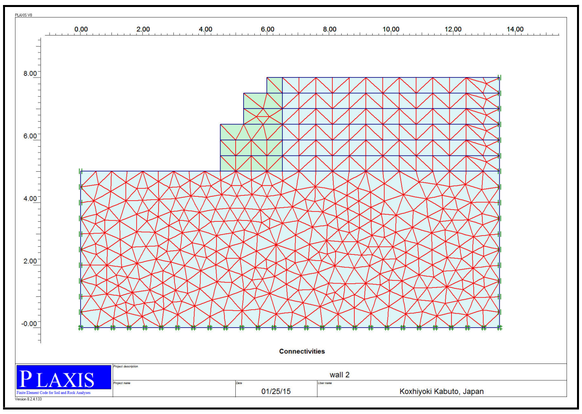


Figure 2: Finite element model-2

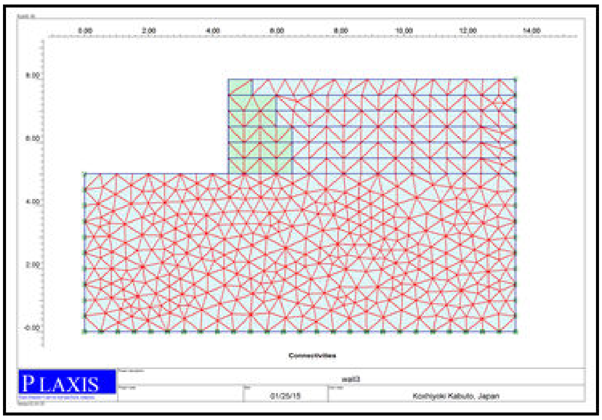


Figure 3: Finite element model-3

Suggested construction sequences are, (i) backfilling after wall construction (construction method 1) (ii) backfilling parallel to wall construction (construction method 2).

In backfilling after wall construction (construction method 1), calculations for the multi-phases numerical analysis were performed using the stage construction procedure. The calculations were executed in 8 phases including the wall construction and surcharge loading, starting from the initial state where the wall is constructed, each phase corresponding to a single loading of 0.5m of backfilling, yielding a total of 6 layers (phases), and ending with the state where all finite element model components, including surcharge loading, were activated. For each stage the calculation progress until the prescribed ultimate state is fully reached.

In backfilling parallel to wall construction (construction method 2), calculations for the multi-phases numerical analysis were performed using the stage construction procedure. The calculations were executed in 7 phases including the surcharge loading, starting from the initial state where the wall is constructed parallel to each phase corresponding to a single loading of 0.5m of backfilling, yielding a total of 6 layers (phases), and ending with the state where all finite element model components, including surcharge loading were activated. For each stage the calculation progress until the prescribed ultimate state is fully reached.

7. Fem Analysis and Results

7.1 Total displacement (movement) comparison

Model	Construction method	Construction stage's movement	
		Clock wise	Anti-clockwise
	1	0-1-2-3	3-4-5-6-7-8
	2	0-1	1-2-3-4-5-6-7
	1	0-1-2-3-4-5	5-6-7-8
	2	0-1,3-4,6-7	1-2-3,4-5-6
	1	1-2-3-4-5	0-1,5-6-7-8
	2	0-1,3-4	1-2-3,5-6-7

7.2 Horizontal displacement plots

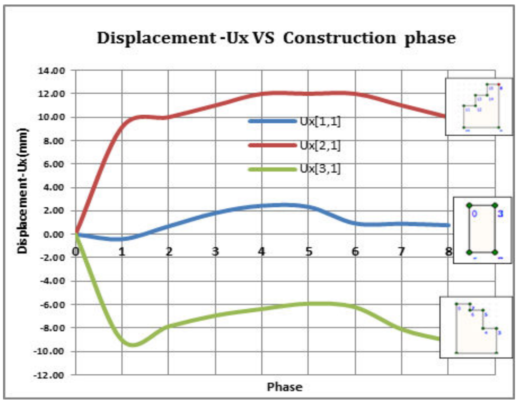


Figure 3: Construction method 1 - backfilling after wall construction (reference to top edge)

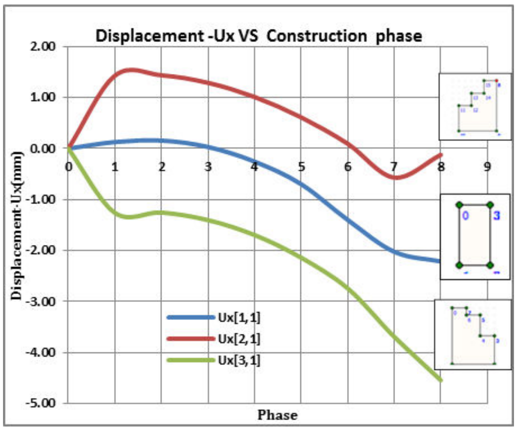


Figure 5. Construction method 1 - backfilling after wall construction (reference to bottom base)

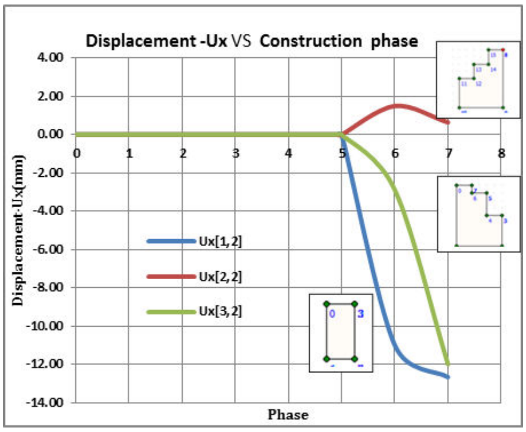


Figure 6: Construction method 2 - backfilling parallel to wall construction (reference to top edge)

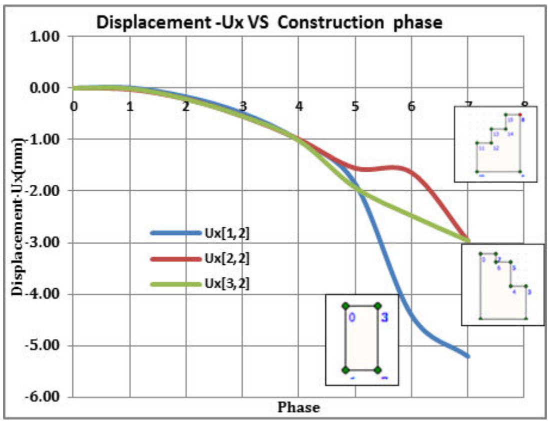
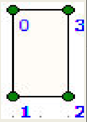
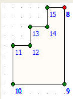
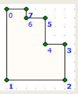


Figure 7: Construction method 2 - backfilling parallel to wall construction (reference to bottom base)

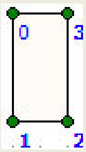
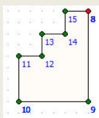
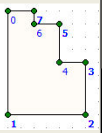
7.2.1 Final displacement analysis in a view

Model	Construction sequence	Horizontal Displacement diagram (backfilling right hand side)	Vertical displacement	Comments
Model 1	1	0.77mm 2.21mm	14.8mm	Ux=+2.98mm
	2	12.67mm 5.21mm	10.7mm	Ux= -7.46mm
Model 2	1	10mm 0.12mm	15.2mm	Ux=+10.12mm
	2	0.64mm 2.96mm	10.7mm	Ux=+3.6mm
Model 3	1	9.106mm 4.544mm	15.2mm	Ux=-4.544mm
	2	12mm 2.96mm	14.8mm	Ux=-9.04mm

7.3 Sliding and overturning analysis

Model	Construction sequences	Dominating factors		Overall dominating factor
		Overturning	Sliding	
	1	1-5	5-8	Overturning - toward backfilling side
	2	3-7	1-7	Overturning and sliding - outward the backfilling
	1	1-8	-	Overturning - toward the backfilling
	2	3-6	1-7	Sliding - out ward the backfilling
	1	1-8 anti clockwise	1-8	Overturning - outward the backfilling
	2	4-7	1-7	Sliding - outward the back filling (high value)

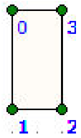
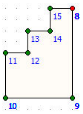
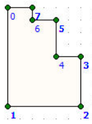
7.4 Bearing pressure distribution

Model	Construction sequences	Maximum bearing pressure(kN/m²)		Pressure distribution	Comments
		FEM	MANUAL		
	1	93.87	195.84	Non uniform	Safe against bearing
	2	103.32		Non uniform	Safe against bearing
	1	81.68	100.01	Non uniform	Safe against bearing
	2	81.76		Non uniform	Safe against bearing
	1	104.46	201.64	Non uniform	Safe against bearing
	2	123.3		Non uniform	Safe against bearing

7.4.1 Indication of Shadings

(red)	Reject
(yellow)	Neutral limit
(green)	Acceptable limit

7.5 Wedge failure angle

Model	Failure wedge angle-Theoretical	Wedge failure angle-FEM	Comments
	58.75°	55°- construction 1 52°- construction 2	**Approximately equal. safer construction**
	58.75°	68°- construction 1 65°- construction 2	**Both safer constructions**
	66°	38°- construction 1 45°- construction 2	**Both show critical conditions**

8. Discussion and Conclusion

Often the design methodology of retaining walls does not take into account the construction sequences, which simulate the process by which the soil and the retaining wall are brought together. In the present investigation, the influence of the construction sequences on the behaviour of mass concrete retaining wall is investigated with three different gravity retaining wall models using FEM. Two different construction sequences were used to evaluate the affect of the construction methods. Out of the three types of walls considered, the third type is found to have the lowest stability. It shows high bottom and top displacement outward the backfilling. Both sliding and overturning are in the same direction. Bearing pressure is 201.64kN/m^2 (BS 8002). When considering wedge failure, the wedge starts from under the base. The wall is likely to fail due to above critical reasons. In addition, the centre of gravity of the wall is toward the outward face of wall. This is the reason for high rotation in anticlockwise direction, which is negative in this instance. **For these reasons, wall type-3 is not preferable in stable construction of high walls.**

Other two gravity walls show stability against backfilling. When we consider the wall type-1, it shows unfavourable horizontal displacement in top and bottom of wall for construction method 1. Both sliding and overturning are outward the backfilling.

Construction method-1 shows smaller top and bottom displacement in opposite directions, however in clockwise direction, which is positive in this instance. Bearing pressure is within the limit. Significant (2.21mm) sliding has increased the stability of the wall. **For these reasons, the construction sequence of method 1, i.e., backfilling after wall construction, is preferable for wall type 1.**

The wall type 2 appears to be the most preferable among all three types of walls. Both construction sequences are preferable for this wall type. In construction method 1, even though overturning is significantly high, it is toward the backfilling, which is a desirable direction. Centre of gravity of wall is toward the backfilling face, resulting in increased stability. Construction method 2 shows a small sliding and overturning tendency. However, its failure wedge angle is smaller than construction method 1. **Therefore, both construction sequences are preferable for wall type 2.**

Finally with this examination, we could conclude that the construction sequence is a critical factor to be considered in the design stage of gravity type walls as our observations clearly demonstrate that the construction sequences influence the stability of the wall both during and after wall construction.

Acknowledgement

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