Stability of Retaining Walls with Compacted Backfills

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SUMMARY A new technique referred to as the "Nodal Displacement Method" - based on the Finite Element Method - was developed at Monash University for the evaluation of the stability of geotechnical structures and slopes. A compaction simulation algorithm was also developed and incorporated with an elastoplastic finite element model to simulate the compaction of the fill behind retaining walls. This paper describes the application of the nodal displacement method to evaluate the stability of retaining walls where the backfill has been compacted.

1. INTRODUCTION

In a companion paper submitted to this conference by Donald and Goh (1992), difficulties with traditional approaches to retaining wall stability are discussed and a new method, the "Nodal Displacement Method", based on finite element calculations, is presented and discussed. Donald and Goh's approach simulates backfilling behind gravity and semi-gravity walls and compares safety factors calculated from the new and traditional methods.

The essence of the Nodal Displacement Method (NDM) is that strength parameters c and $\tan\phi$ are progressively multiplied by a variable N ($\gtrless 1$) until excessive calculated deformations occur and the Safety Factor, F, is then taken as $1/N_{critical}$.

Where compaction of the backfill is required, more complex simulation algorithms are needed for satisfactory modelling of field behaviour. The present paper presents such a compaction model which leads to distributions of lateral stress on the back of the wall which are quite different from those for the case of non-compacted backfill. The compaction induced stress profiles are intended mainly for the purpose of structural design and their use in conventional stability analyses will only provide a safety factor against the initiation of movements leading to failure and not a safety factor against overall wall collapse.

More realistic assessment of wall stability may be obtained through extensions to the Nodal Displacement Method. The compaction simulation model introduces several important new variables and, in addition to factoring c and $\tan\phi$, these values must be adjusted in a sensible manner for meaningful analysis. In this paper the application of the modified method to gravity walls with compacted backfills is discussed and several examples presented. The influence of factors such as foundation stiffness is also illustrated. The stability of walls with compacted backfills is compared to those with non-compacted backfills.

2. COMPACTION SIMULATION MODEL

Broms (1972), Ingold (1979) and Seed & Duncan (1983) have proposed various models for compaction of fill behind retaining walls. The fundamental idea of Kulathilaka's (1990) model was derived from the Seed and Duncan model. Modifications made to produce a close simulation of the compaction process and the techniques employed in incorporating the model with the Elastic-Ideally Plastic Finite Element model are briefly outlined below.

Compaction effort applied at the surface by a plant is simulated by the application of a lateral stress profile at the current surface level. The compaction simulation model interpolates the compactor imposed lateral stress $\Delta\sigma_{x,c}$ for the soil element under consideration, using the depth to the Gauss points of the element.

2.1 Loading of an Element

Prior to the current compaction increment the lateral stress level of a typical soil element in the backfill will be in a K_o state (A_1), higher than K_o state (A_2) or lower than K_o state (A_3) as in Figure 1. If the initial stress state of the element is either K_o or lower than K_o, lateral stress and vertical stress will increase on a path parallel to the K_o line, while the compactor is still on the surface. If the initial stress state is higher than K_o the stress increase will follow a path of slope K_3 till it meets the K_o line and follow the K_o line thereafter.

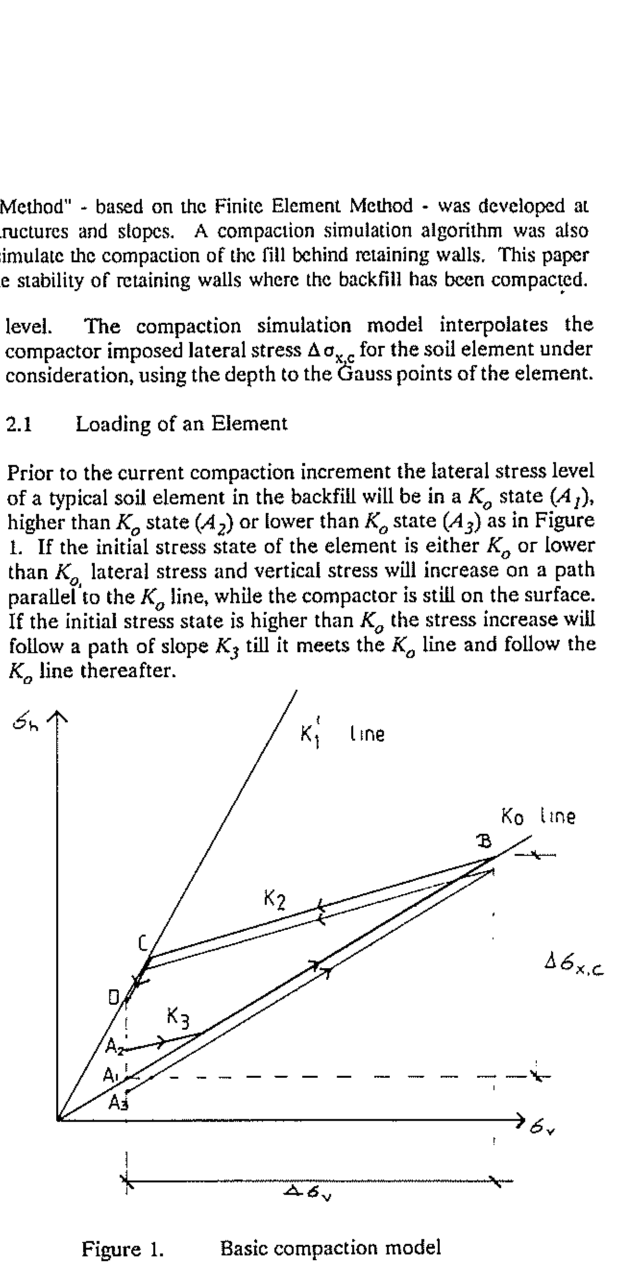

Figure 1. Basic compaction model

When the stress state is K_o or lower, the lateral stress will increase by $\Delta\sigma_{x,c}$ while the compactor is still on the surface. When the initial stress rate is higher than K_o the lateral stress state will be smaller due to the initially stiffer response. This is implemented by computing an "equivalent vertical driving stress" $\Delta\sigma_v = \Delta\sigma_{x,c}$.

2.2 Unloading Due to the Removal of the Compactor

Stress release in both the vertical and horizontal directions will take place along the K_2 line during the removal of the compactor.

If the unloading path meets the K'_1 line prior to the reduction of the vertical stress to the overburden values, unloading will follow K'_1 line thereafter. Thus an unloading path of the form "B-C-D" will be followed. The residual lateral stress increase is denoted by $\Delta\sigma_{x,r}$. The model identifies the present stress state of an element and various numerical procedures are employed to capture the turning points and to implement the stress path.

2.3 Numerical Techniques Used in the Simulation

Purely for analytical purposes, lateral stress is separated into a geostatic component ($\sigma_{x,geo}$) and a compaction induced stress component ($\sigma_{x,comp}$). The latter is obtained by adding up the compaction induced residual lateral stresses. The remaining part is taken as the geostatic stress.

By taking all the soil elements through the model, the residual lateral stress increases are computed and the total force vector on the wall is assembled. Deformations in the soil-structure system are then computed by the finite element model. The resulting stress rearrangements are then computed by the finite element model subjected to the conditions imposed by the compaction simulation algorithm. When there are stress relaxations due to wall movements, geostatic and compaction induced stress components are expected to share the reductions proportionally to their present values.

The number of passes of the compactor at a certain fill elevation is modelled in a single numerical increment. With ongoing compaction soil elements closer to the surface are expected to regain the lateral stresses relaxed through wall movements. The geostatic stress component of the element is compared with the compactor imposed stress for the element. If the latter is larger than the former, the soil element is taken to be close enough to the surface to regain the relaxed stresses.

3. POSSIBLE COMBINATIONS OF PARAMETER REDUCTION

In addition to the standard soil strength and stiffness parameters (c, ϕ, K_o and E), three other parameters (K'_1, K'_2 and K'_3), are introduced by the compaction simulation algorithm. These compaction model parameters govern the lateral stresses that could be sustained in the soil, the compaction introduced forces acting on the wall and the $\Delta\sigma_h$ vs $\Delta\sigma_v$ relationship during loading/unloading. Therefore the reduction of specific parameters by the "Nodal Factor" is more complicated than for a simple backfill case and could be performed in several ways. Extensive preliminary investigations were carried out to identify the critical variables and most appropriate method of parameter reduction.

The parameter K'_1 is a function of ϕ and controls the amount of residual compaction induced stress that can be sustained in the element. If the K'_1 values are also reduced according to the reduced ϕ value, $\phi_{red} = \tan^{-1}(N \tan\phi)$, the residual lateral stress increase due to compaction and thereby the compaction induced forces on the structure will also be reduced. This will in turn cause a reduction in wall movements. Some reduction in "lateral stress relaxation due to the wall movements" could also be expected. One series of analyses was performed where all the parameters (c, ϕ, K'_1) were reduced.

It should be borne in mind that the reduction of properties through a nodal factor is only a hypothetical phenomenon. The actual soil does not undergo any reduction in strength or stiffness. Thus the actual sustainable residual lateral stress increase due to compaction, and therefore the compaction induced forces on the structure would not change, regardless of the nodal factors used in the analyses. To be compatible, the c and ϕ values used in the stress level computations in the compaction simulation algorithm, also should not be reduced. Therefore another series of analyses was done without reducing c, ϕ and compaction model parameters in the compaction simulation algorithm. K_2 and K_3 values correspond to unloading and reloading slopes. These values, together with the K_o value, were not changed, as factoring was shown by the preliminary investigations to give erratic results.

Lateral stress increase due to compaction was found to be dependent on the direction of the movement of the compactor

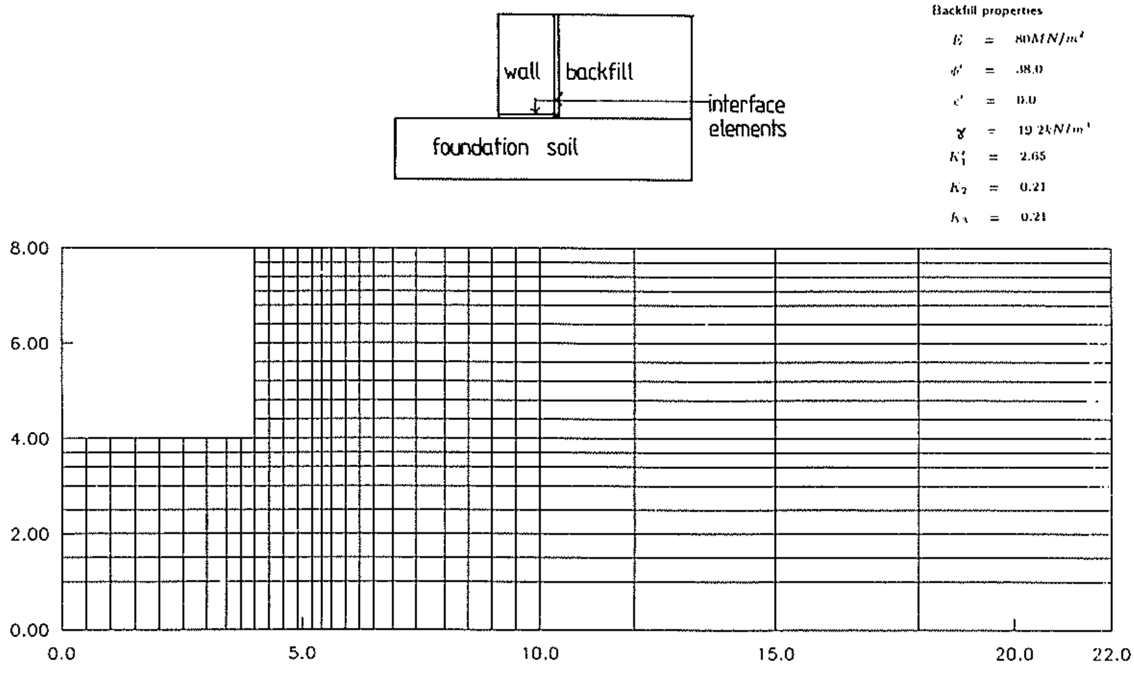

Figure 2. Finite element mesh and soil properties

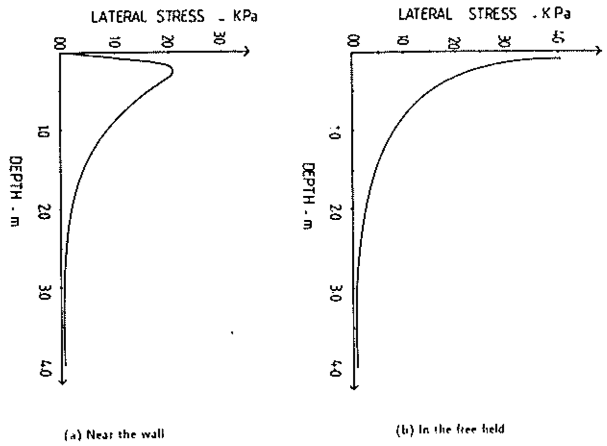

Figure 3. Compactor induced stress profiles

(D'Appolonia et al (1969)). As the intermediate principal stress is also an important parameter in the elastic ideally plastic finite element formulation, any assumption on residual stress increase parallel to the wall is also a critical factor. This aspect is discussed in detail in Kulathilaka (1990). In the examples presented in this paper, even compaction is assumed in all directions and the lateral stress increase parallel to the wall is taken to be as same as that normal to the wall.

4 EXAMPLES

The sample problem used for this analysis is a 4.0 m high gravity retaining wall with a width of 1.4 m. Backfilling behind the wall is assumed to have taken place in 11 increments, therefore there will be 11 compaction increments in addition to the compaction of the foundation layer. The geometry and FE idealization of the problem are depicted in Figure 2. All the wall/soil interfaces were modelled with one dimensional interface elements. Compactor imposed lateral stress profiles used for the examples are depicted in Figure 3. The backfill was assumed to be a cohesionless soil. Two different foundation conditions were assumed; a "stiff" foundation with a $E_{fdn}/E_{backfill}$ ratio of 4 and a "soft" foundation soil with the same modulus as the backfill. Backfill and foundation properties used are shown on the diagrams.

In some cases only the backfill properties were varied, whereas both the backfill and foundation properties were varied in other cases.

4.1 Wall on a "Stiff Foundation"

Strength and stiffness parameters of the backfill and the foundation and the compaction model parameters are reduced in three different ways with this wall on a stiff foundation. If the conventional FOS against overturning is computed with the assumption of active conditions at the back of the wall a value of 2.2 is obtained. The lateral stress profile at the back of the wall with compaction simulation is depicted in Figure 4. Using this working stress profile a FOS of 1.2 against overturning is obtained, a considerably lower value as would be expected.

4.1.1 Backfill parameters varied. Compaction model parameters kept constant. Foundation properties kept constant.

In this series only the backfill and interface strength properties were reduced. Foundation properties as well as the compaction model parameters were kept constant. The Nodal Factor, taken here as 1/N, could be increased beyond 3.4 without causing any abrupt increase in the wall displacements (Figure 5). The strong foundation soil has resisted rotation type wall movements induced

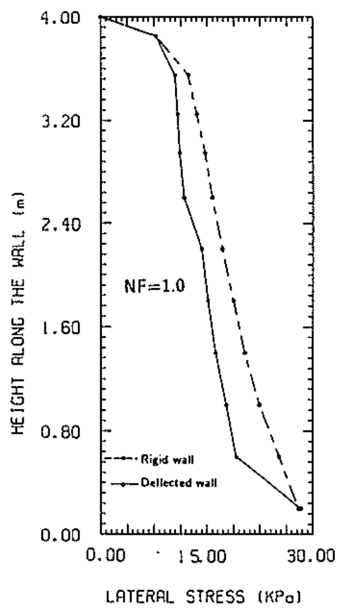

Figure 4. Lateral stresses - compacted fill

by the compaction induced nodal forces. The unchanged compaction effect (due to unchanged compaction model parameters) imposed some strengthening effect enabling larger theoretical reductions of backfill strength properties before failure.

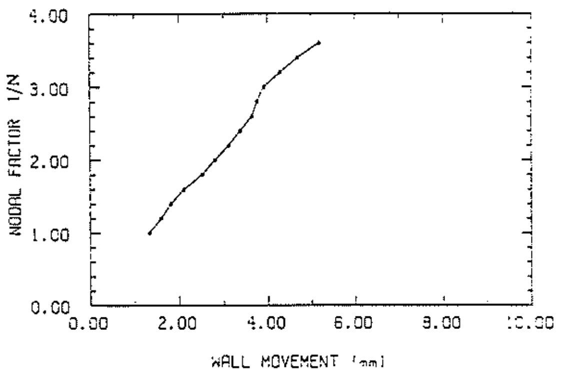

Figure 5. NDM plot - reducing backfill properties

4.1.2 Backfill and compaction model parameters varied. Foundation properties kept constant.

In this series compaction model parameters of the backfill were also reduced by the nodal factor, together with the strength and stiffness properties. Reduction of the parameter K'_l reduced the residual compaction induced stresses and thereby reduced the strengthening effect due to compaction. After a nodal factor of 2.52 was exceeded the numerical solution did not converge. If the incremental construction process was simulated allowing high unbalanced loads when the solution was failing to converge, a large increase of displacement was calculated as depicted in Figure 6. This displacement value is not exact; nevertheless it indicates that the nodal factor of 2.52 corresponds to the inception of failure. Total displacement vectors indicate that the wall movements are predominantly horizontal and soil movements contain a very significant vertical component (Figure 7).

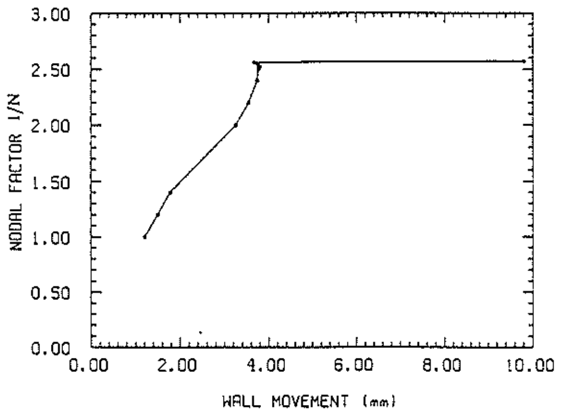

Figure 6. NDM plot- vary backfill and compaction model parameters

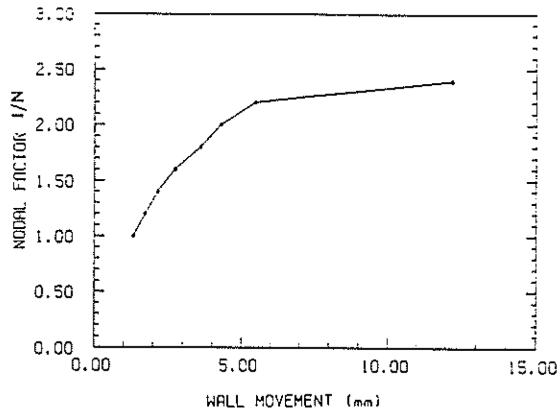

Figure 8. NDM plot - vary backfill and foundation properties

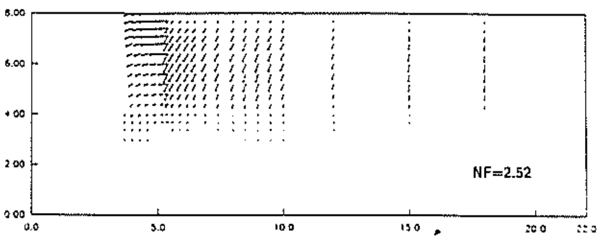

Figure 7. Total displacement vectors

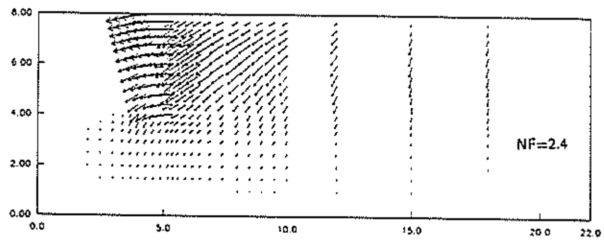

Figure 9. Total displacement vectors

4.1.3 Backfill and foundation properties varied.
Compaction model parameters kept constant

In this series of examples the foundation strength and stiffness parameters are also reduced by the same nodal factor as for the backfill properties. However, the compaction model parameters were not reduced. Thus the backfill and the foundation will sustain residual compaction induced stresses as for the real soil. The compaction induced forces on the wall will be the same while the strengths are being reduced. As with the previous set the displacement at the nodal factor of 2.4 was achieved while tolerating high unbalanced loads. Thus a nodal factor of between 2.2 and 2.4 indicates the inception of failure (Figure 8). The total displacement vectors at the nodal factor of 2.4 outlined a predominantly overturning type failure (Figure 9).

4.2 Wall on a "Soft" Foundation

In these examples the wall was assumed to be founded on a soil with the same modulus as the backfill. The strength of the foundation soil was also decreased from that in the initial examples. The reduced stiffness and strength of the foundation yielded lower safety factors as illustrated by the following examples. The observations are compared with a non compacted backfilling on the same foundation.

Since the CP 2 definition of FOS on overturning does not account for foundation stiffness, this wall will also have a FOS of 2.2 against overturning (i.e. active stresses are assumed). The lateral stress distribution at the back of the wall with the compaction simulation is presented in Figure 10. Using these FE working stresses a FOS of 1.36 - marginally higher than the previous case - was obtained. This is because of the smaller lateral stresses resulting from increased wall movements.

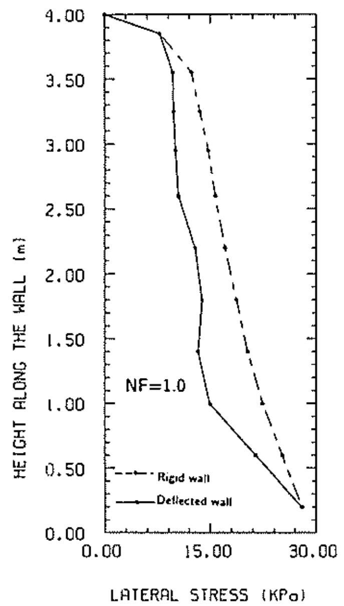

Figure 10. Lateral stresses - "soft" foundation

4.2.1 Compaction model parameters kept constant.
Foundation properties kept constant.

In this series of computations only the strength properties of the backfill are reduced by the nodal factor. Neither the foundation properties nor the compaction model parameters were altered. After a nodal factor of 1.6 large movements were observed (Figure 11).

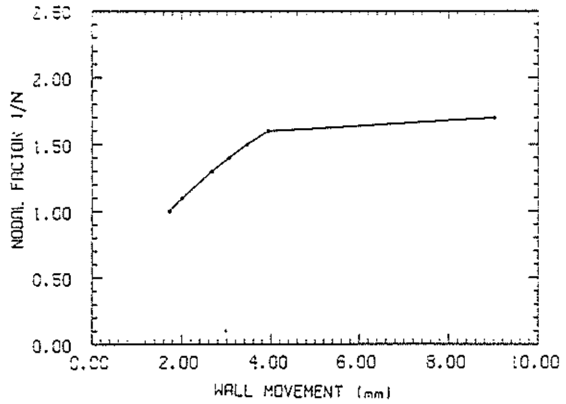

Figure 11. Soft foundation - vary backfill only

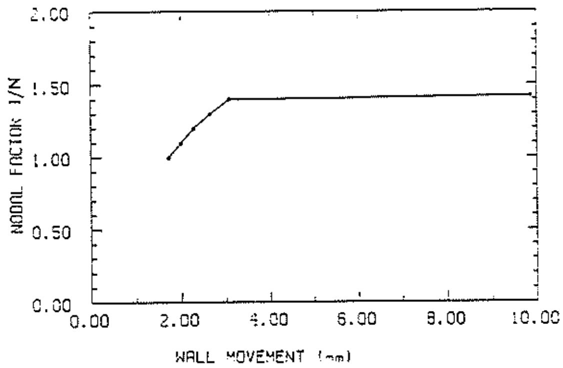

Figure 12. Vary backfill and foundation properties

4.2.2 Compaction model parameters kept constant. Foundation properties are also reduced

Foundation properties were also reduced by the nodal factor in this set of problems in addition to the backfill and interface properties. The compaction model parameters corresponding to both the foundation and the backfill were kept constant. As can be seen from Figure 12 the safety factor was 1.4 - slightly less than for the previous case.

4.3 Non-Compacted Fill on Soft Foundation

Backfilling behind the wall without compaction is simulated for the wall founded on softer soil. Founding soil was also not compacted prior to the backfilling.

The lateral stress profiles for the compacted and non compacted fill when the nodal factor is 1.0 are compared in Figure 13. Using the much smaller FE lateral stress profile of non compacted backfill a FOS against overturning of 1.78 was achieved from the CP2 analysis.

The results of the two nodal displacement method analyses with and without the reduction of foundation properties are presented in Figure 14 and Figure 15 respectively. The safety factors of 1.17 and 1.32 achieved in the two instances are much smaller than the value of 1.78 computed using FE working stresses at the back of the wall. Both safety factors are smaller than the corresponding ones for the compacted backfill. This highlights the strengthening of both the foundation and backfill due to the compaction.

It is interesting to note that for the compacted backfill the NDM safety factor was larger than that computed using the FE working stresses and for the non compacted backfill it was the other way.

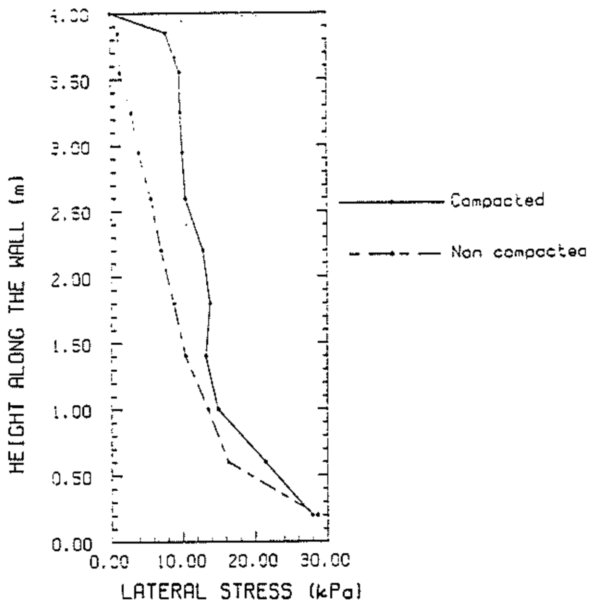

Figure 13. Lateral stress comparison

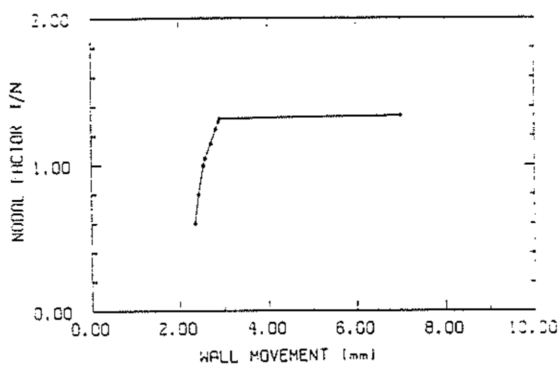

Figure 14. Non-compacted fill; vary backfill properties only.

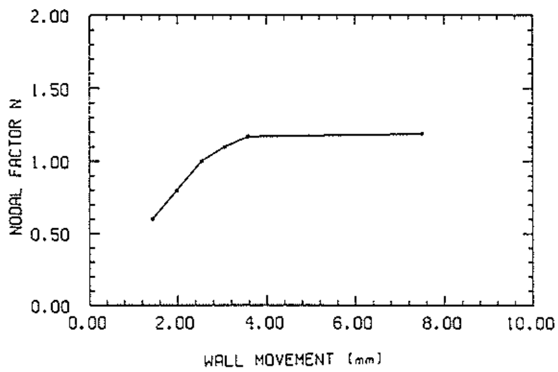

Figure 15. Vary backfill and foundation properties

5. DISCUSSION

Safety Factors or critical Nodal Factors ($= 1/N_{cr}$) for a range of problems are summarised in Table I. The information is not comprehensive enough for definitive design rules to be formulated, yet some interesting trends emerge.

TABLE I

COMPARATIVE SAFETY FACTORS

Foundation Condition	Method of Evaluation	Conditions Used	FOS or $1/N_{cr}$
Stiff or Soft foundation	CP 2 (overturning)	Non Compacted fill. Use active earth pressures.	2.20
Stiff fd'n	FE stresses in CP2 def'n	Compacted fill	1.10
Stiff fd'n	Nodal Displ. Method	Only backfill strength prop. varied	> 3.4
Stiff fd'n	Nodal Displ. Method	Backfill strength and comp model prop. varied	2.52
Stiff fd'n	Nodal Displ. Method	Backfill and foundation strength prop. varied	2.30
Soft fd'n	FE stresses in CP2 def'n	Compacted fill	1.36
Soft fd'n	Nodal Displ. Method	Only backfill strength prop. varied	1.60
Soft fd'n	Nodal Displ. Method	Backfill and foundation strength prop. varied	1.40
Soft fd'n	FE stresses in CP 2 def'n	Non compacted fill. Only backfill strength prop varied	1.78
Soft fd'n	Nodal Displ. Method	Non comp. fill. Only backfill strength prop. varied	1.32
Soft fd'n	Nodal Displ. Method	Non comp. fill. Backfill and fd'n strength prop. varied	1.17

As expected, the use of F.E. calculated stresses (for N = 1, i.e. the actual field state) in conventional Code analyses leads to unrealistically low values of F. This is because the analyses make no allowance for stress release as the wall yields under the influence of the lateral stresses.

For the "stiff" foundation soil the NDM analysis with varying backfill and foundation strength gives an answer close to the CP2 analysis (2.30 cf 2.20), but this is at least partly fortuitous, as the foundation soil strength does not enter into the Code analysis. The NDM displacement vectors indicate basically overturning behaviour, which agrees with the assumption on which the CP2 value was calculated. Varying only the backfill strength yields an unrealistically high F at > 3.4 and with the present state-of-the-art of the NDM considerable engineering judgement is required to decide which parameters should be varied for any particular wall.

For the "soft" foundation soil with compacted fill a similar pattern emerges, though varying only backfill properties does not produce such a large change in F as for the stiff soil. The three values in Table I for soft foundation soil and compacted backfill are all in the range F = 1.5 ± 0.1, but the conventional CP2 value for overturning would of course remain at 2.2. For non-compacted backfill the NDM critical Nodal Factors are significantly reduced, because of the lower stress and hence lower strengths in the retained soil. It would seem on the limited evidence presented that foundation stiffness, which is ignored in conventional methods, has a major influence on the deformation pattern and hence, through displacement induced stress relaxation, on the safety factor.

6. CONCLUSIONS

Investigations have been described which demonstrate the application of the Nodal Displacement Method to calculations of the stability of retaining walls. For some situations the method yields values comparable with conventional analyses, but in other cases significant differences arise, particularly for softer foundation soils. Unlike conventional methods, the NDM does not require assumptions as to the failure mechanism and can readily model construction sequences including compaction-induced stresses. The complex wall-soil interaction effects which occur in practice are automatically allowed for and, with further refinement, the method could provide a useful alternative to existing, less than totally satisfactory design methods.

7. REFERENCES

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