ANALYSIS OF TWO-DIMENSIONAL STRUCTURES USING SLOPE STABILITY PROGRAMS

by

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MOTS-CLEFS

Mode de rupture géotechnique, équilibre limite, méthodes numériques, stabilité

1. INTRODUCTION

In 2005, the Port Engineering Technical Committee of the Spanish Section of the International Navigation Association (PIANC), agreed to set up a Task Force with a view to 'compare the limit equilibrium and numerical method stability calculation programs available on the market for studying failure modes that are a result of deep sliding, sinking and plastic overturning', in situations where the latter phenomena affect such linear structures as quays or breakwaters.

The relevance of this study is fully justified by the fact that problems frequently arise in the world of port engineering when it comes to having to calculate the stability of structures (such as, for example, caissons supported on embankments composed of strata with different resistance characteristics) using commercial programs which are based upon different calculation methodologies that can lead to greatly contrasting results.

On more than one occasion we have seen how the safety coefficients that are obtained for a failure mode depend to a great extent upon both the program and the methodology used. In fact, one single program may even yield very different results depending upon how the grid has been modelled or upon the hypotheses considered (for which, up to the present, there have not been any clear criteria).

In view of the enormous dimensions of port structures it is essential to optimise the design so that the economic resources of the taxpayers in general and the Port Authorities in particular, can be put to the best possible use. We believe that it is necessary to invest in engineering to cut down on the overall costs of port investments.

2. ACTIVITIES TO BE PERFORMED BY THE TASK FORCE

The following activities have been undertaken in order to achieve the Task Force's initial objectives:

- Theoretical reflection and pre-analysis of the current state of the art.
- Discovering which commercial programs are most frequently used by Spanish engineers and selecting a large number of technicians with experience in the use of different stability calculation programs using limit equilibrium and numerical methods. It has also been considered advisable that several independent technicians use the same program, to solve the same problem, in order to find out how the results are influenced depending on the person who inserts the data.

- Proposing a standard stability problem that has to be solved by all the members of the Task Force.
- Assessment and comparison of the results.
- Conclusions and proposals for the future.

3. STATE OF THE ART OF LIMIT EQUILIBRIUM METHODS

The use of limit equilibrium methods is endorsed by the extensive experience that has been obtained in using them successfully to solve slope stability problems.

Currently the use of limit equilibrium methods is widespread for calculating ultimate bearing capacities of quays and harbour breakwaters as well as plastic overturning phenomenon.

However, the use of these methods for shallow foundations causes serious problems (See Reference 1 in the bibliography), especially when only circular failure curves are evaluated.

Other authors, such as John Krahn, the person responsible for the SLOPE commercial program, warns of the inherent limitations to these methods, because they do not take into account the compatibility of deformations and displacements (See Reference # 2 in the bibliography). Therefore, they must be employed with special attention to stress concentration situations and the sensitivity of the results to the variation of certain parameters of the problem, such as, for example, the value of λ (relationship between the shear strength and the normal strength between elements) should be taken into account.

However, he recommends methods that take into account not only moment equilibrium, but also the horizontal forces, such as the Morgensten-Price Method and the Spencer Method. Krahn reminds us that these methods have been devised to deal with problems where the main load is gravitational in nature. When this is not the case (such as a footing), or when there are point loads, increased precautions should be taken.

In view of all the aforementioned, and in awareness of the fact that "these methods have their shortcomings and are perhaps being applied to situations that are beyond their original aims", he proposes that before such methods are used, the problem be analysed, so that insight can be obtained regarding the stress distribution, (as well as, in our opinion, insight concerning the potential failure lines), for example, conducting an elastic analysis with finite elements, so that it will then be possible to find a stress distribution and a similar failure line using the limit equilibrium method. If this is done, the new technologies will be brought into use while at the same time be based on the knowledge gathered from past experience.

Thanks to these concerns, several works have surfaced (See Reference 3 in the bibliography), dealing with the different safety coefficients obtained for the ultimate bearing capacity of a harbour caisson.

Reflecting upon these recommendations, the following question immediately springs to mind, and it is this question that we will be considering throughout this article: Is it sufficient to work only with limit equilibrium methods or should we supplement them with another type of numerical analysis? And, to take the question even further, have we reached the stage where we are in a position to use only numerical methods or should we still carry on working with the limit equilibrium method?

4. STATE OF THE ART OF NUMERICAL METHODS

Although these types of methods have been used ever since the end of the 1960s (to be specific, the reference to the use of the Finite Elements Method for geotechnics dates back to 1967, where it was proposed at the Berkeley Slope Stability Conference), experience is not as extensive nor as conclusive as it is for the Limit Equilibrium Methods. Originally, numerical methods were used exclusively to calculate deformations and displacements.

Duncan (See Reference 4 in the bibliography), stated that an initial difficulty with these methods lay in the fact that they were complex in nature. However, relatively simple commercial programs are now available on the market. In spite of this, when it comes to interpreting and analysing the results obtained, extensive knowledge is required, not only of the numerical techniques used in the programs but also of the geotechnical aspects of the problem in question.

If such powerful methods are to be used correctly, it is first necessary to define the stress-deformation relations inherent to the material, and the user also has to be aware of the initial stress state, the way the construction process is going to develop, etc.

As it is a relatively new method, it will be necessary to select criteria concerning resistance reduction techniques, failure control parameters, etc.

The great advantage of these methods lies in the fact that the calculation result produces the worst failure mechanism. That is to say, the results define the failure in a natural way, on the basis of the stress state and the compatibility of deformations for the problem being examined. They can serve as an excellent guide (both for finding the worst failure line and the stress state of the system) before limit equilibrium methods are used for analysis purposes.

5. ACTIVITIES PERFORMED BY THE TASK FORCE

5.1 General approach

An initial proposal was made to the members of the Task Force in which they would endeavour to solve six standard problems: global stability, sinking failure, and plastic overturning, each on two potential natural types of ground: zones composed of granular material with long-term behaviour, logically using long-term parameters (which throughout this article will be referred to as 'long-term situations'), and zones composed of cohesive material with short-term behaviour (which we will refer to as 'short-term situations').

The standard global stability problems are defined in the following figures (the geometry for the standard sinking problems and plastic overturning problems is the same as in the following figures, but the caisson, the fill, and the external loads are replaced by the equivalent resultant on the mound).

PORT ENGINEERING TECHNICAL COMMITTEE

ANALYSIS OF TWO DIMENTIONAL STRUCTURES THROUGH SLOPE STABILITY PROGRAMS

1 DEFINITION OF THE MATERIALS

LAYER	DENSITY (t/m^3)			COHESIVE		GRANULAR	
	Dry	Saturated	Submerged	C`(t/m^2)	φ (°)	C`(t/m^2)	φ (°)
1 Concrete / Superstructure	2,300	2,300	1,275	100,00	70,00	100,00	70,00
2 Caisson	2,200	2,200	1,175	100,00	70,00	100,00	70,00
3 General Fill	1,700	2,050	1,025	0,00	30,00	0,00	30,00
4 Rockfill embankment	1,700	2,100	1,075	0,00	40,00	0,00	40,00
5 rubble mound	1,700	2,100	1,075	0,00	45,00	0,00	45,00
6 Sandy substratum	1,800	2,100	1,075	0,00	34,00	0,00	34,00
7 Sludge	1,700	1,700	0,675	1,00	0,00	0,00	25,00
8 Clay 1	2,000	2,000	0,975	10,00	0,00	0,00	30,00
9 Clay 2	2,100	2,100	1,075	20,00	0,00	0,00	33,00

Density of Water (row):	1,025	t/m^3
Exterior side Water level:	0,500	
Interior side Water level:	-0,500	
Crest Elevation:	2,700	
Water depth:	-14,000	
Caisson position:	15,000	m
Caisson wall width:	11,500	m
Footing span:	1,000	m
Mound Height:	2,000	m

For all materials:			
Modulus of Elasticity	E =	81,82	MPa
Transversal Modulus of Elasticity:	G =	30,00	MPa

Table 1: Definition of the materials that are involved in the standard problems posed

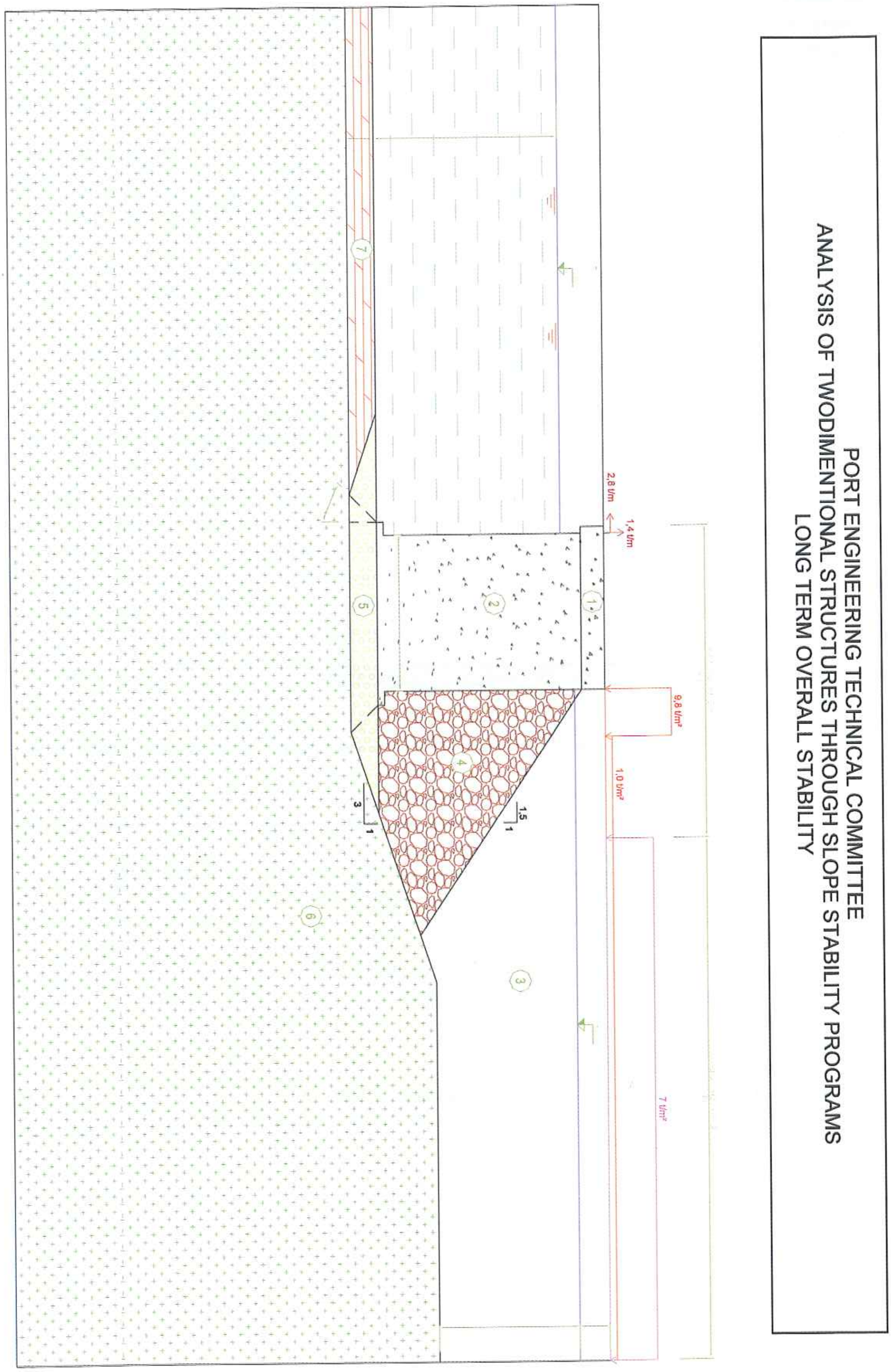

Figure 1: Geometry for the problem known as 'Long-Term Overall Stability'

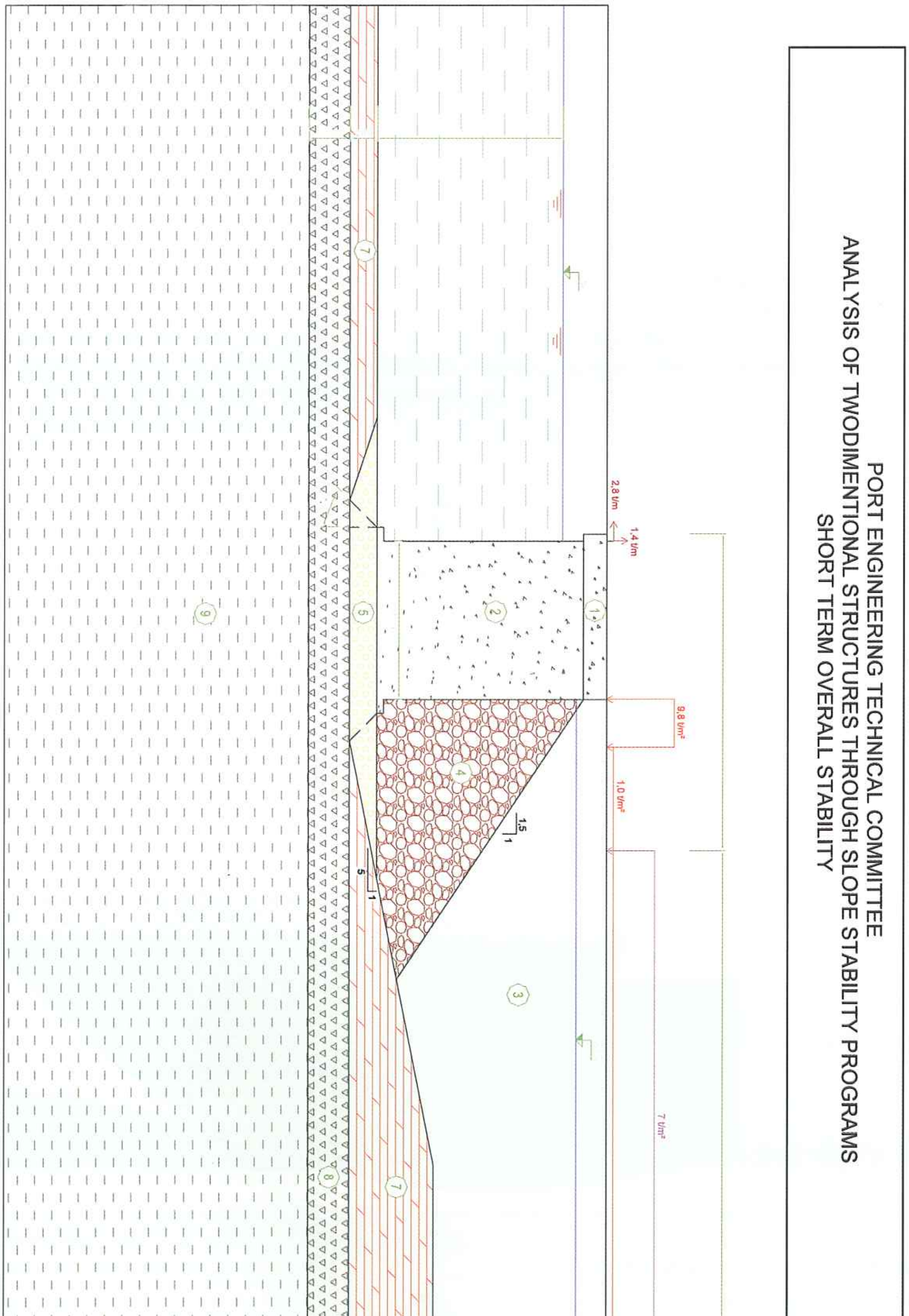

Figure 2: Geometry for the problem known as 'Short-Term Overall Stability'

5.2 First results and lines of activity

Seventeen solutions were originally presented, of which:

- 14 were solved using limit equilibrium methods, of which 11 used the SLOPE Program and 3 used the SLIDE Program.

The following methodologies were used for these 14 solutions: 8 were solved using the Morgenstern-Price Method; 3 were solved using the Spencer method; and the remaining 3 were solved using the Bishop Method.

- 3 were solved using numerical methods: 2 of them with the PLAXIS Program, and 1 with the FLAC/SLOPE Program.

The following conclusions were drawn from the analysis of these 17 reports:

1. The results were very heterogeneous, in the comparison of LE methods.

The following graphs show some of the different results presented by one single company using both a limit equilibrium method and a numerical method, of which indicated that the failure surface is more likely to be flat than circular.

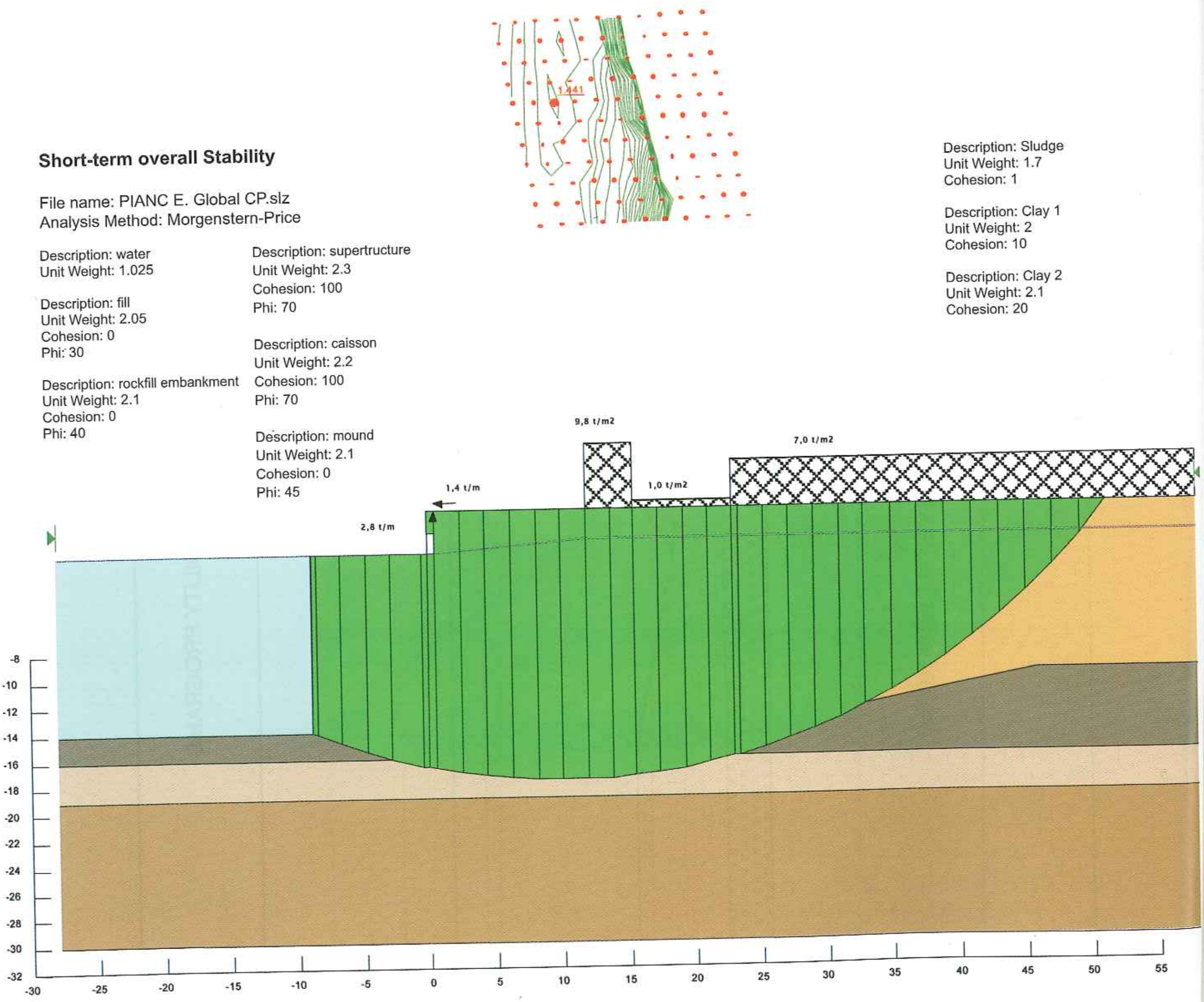

Figure 3: Result obtained using limit equilibrium methods for the short-term overall stability. The safety coefficient was 1.44

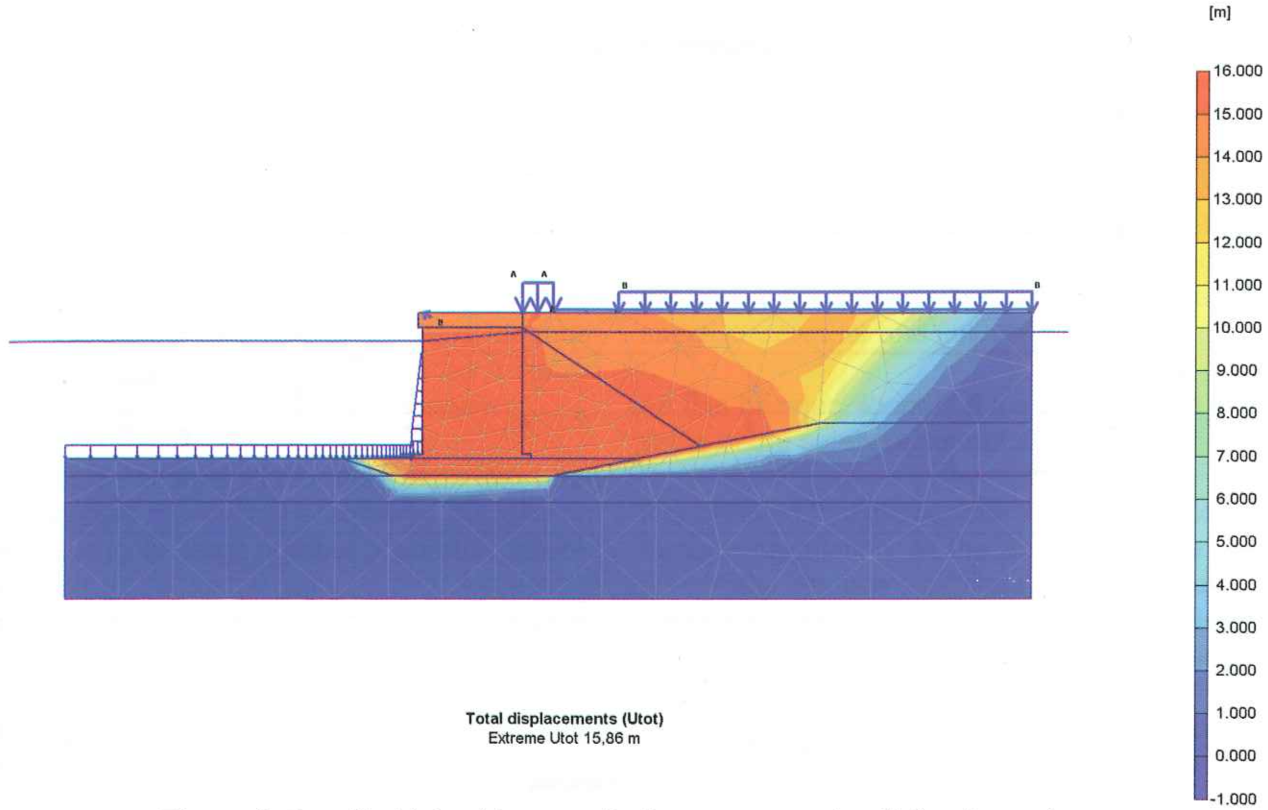

Figure 4: Result obtained by one single company using finite elements. The safety coefficient was 1.05

It is clear that the curve obtained by finite elements better defined the failure mechanism that gave rise to the safety coefficient.

As has already been pointed out, the heterogeneous nature of the results could also be due to the different ways in which different people approach the task of defining one single problem: the way the water is poured in, the way an equivalent footing is defined, etc. As a result, a decision was taken to conduct a Comparative Study in which these factors would be analysed using both the SLOPE Commercial Program and the SLIDE Program. The next section contains a summary of the contents of these studies.

2. Lacking in problems solved by numerical methods.

A decision was taken to increase the number of cases solved by these methods.

5.3 Comparative study of Limit Equilibrium Methods

After the Task Force members that had used limit equilibrium stability programs (SLIDE and SLOPE) and different calculation methods (Bishop, Spencer, Morgenstern-Price) had solved the standard problems, it could be observed that, even for one single program, there were still great disparities in the safety factors obtained.

In the light of the large number of factors that played a part in obtaining the safety coefficient, it was decided to conduct a sensitivity study so that a check could be made on the effects of those factors that the Task Force considered to be most relevant when it came to obtaining a solution: modelling the piezometric level and the water level, applying vertical and horizontal loads, and the shape of the slip surface; the conclusions reached are included in subsequent sections.

The next figure 5 on the next page shows the results of the same calculation made by different companies, forming part of the Task Force.

5.3.1 Modelling the piezometric level

Two methods are available for modelling the piezometric level: either using a water table (location of water surface) and considering saturated densities in the ground, or not considering the water and working with submerged densities (plus the pore overpressures due to the filtering network).

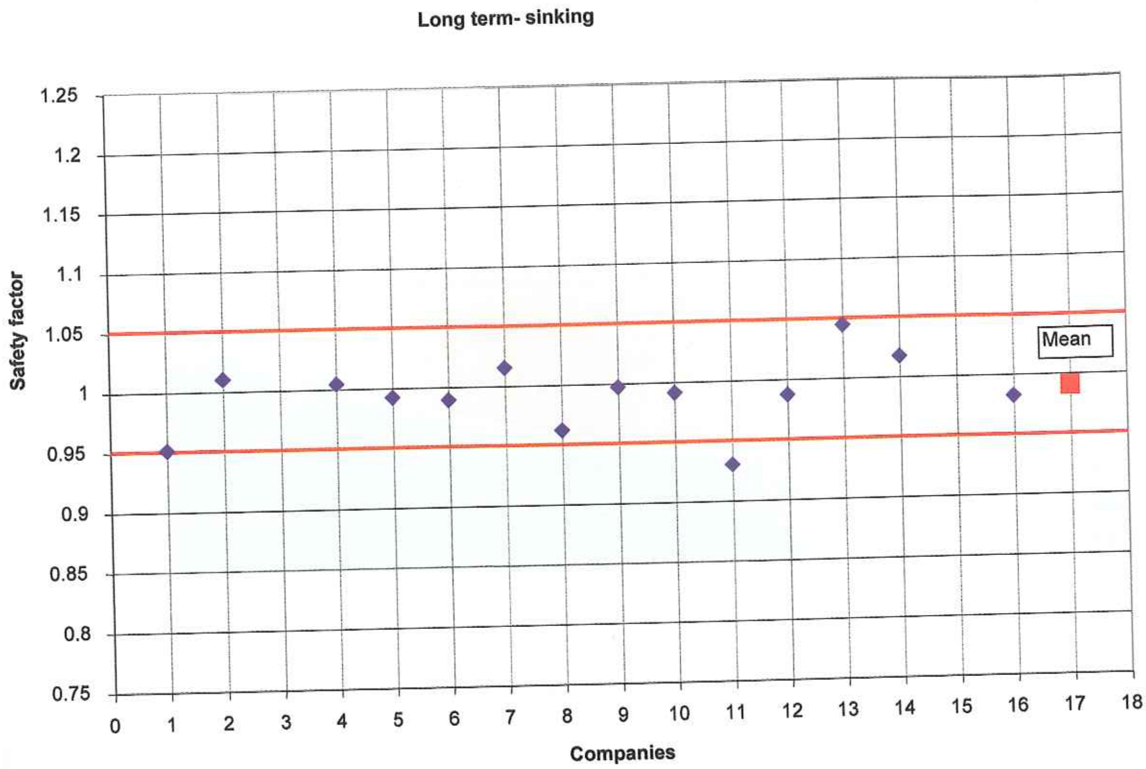

Figure 5: Graph of Safety factors achieved from individual companies for long term sinking analysis

The conclusion reached was basically that the numerical results obtained from the two methods for making the calculations were virtually identical, (if there is no filtering network it should be due to the lack of difference in level between the exterior and interior water levels), although when modelling the piezometric level to check for the ultimate limit states, it can be recommended that the saturated densities method ought to be used for overall stability problems and the submerged densities method should be used for the sinking and plastic overturning limit states.

5.3.2 Modelling vertical and sloping loads

The ultimate limit state study requires stability calculations to be made in which vertical and sloping loads have to be modelled. The modelling of these loads is generally done with the applications that form part of commercial programs, which enable the user to insert point loads that are either concentrated or distributed at different points on the grid.

The cases analysed have made it possible to demonstrate that when the loads are applied by concentrated point loads, problems might arise with the calculation programs when considering the loads that are actually applied for the numerical solution. It was demonstrated that those programs were particularly sensitive to the way the loads were arranged with respect to the failure line limit, which in the verification of sinking and plastic overturning failures, coincide with the edge of the footing.

If these types of calculations with concentrated point loads are made, it is essential to individually check the equilibrium of forces on each one of the slices where the loads have been applied. This is the only method of checking that can be regarded as applicable to all the calculation programs.

The aforementioned problems arising from applying the point loads to the end of the footing were detected when analysing the results obtained from the different methods for inserting the loads. Therefore, it is advisable to use the methods that represent the vertical loads as uniform overburdens.

In contrast to SLOPE, SLIDE enables the user to insert a spread uniform load with a specific slope.

5.3.3 Effect of the shape of the slip surface

5.3.3.1 Overall stability

The aim of the limit equilibrium method is to obtain the minimum safety coefficient for the potential failure surfaces examined. The worst slip surface is not always obtained immediately, so it is necessary to conduct a preliminary analysis of the model and the user is required to exercise a certain degree of skill in carrying out this analysis.

This consideration is all the more important when one analyzes the overall stability of the section. This is due to the large number of possible failures that need to be tested without prior knowledge from the user as to which shape or path the worst failure will take. Therefore, many different surfaces with varying geometry (circular, polygonal, and mixed surfaces) and varying surface entrance and exit areas must be tested to seek the worst case.

When the short-term situation was analysed in the vertical dock that was proposed for study purposes, it was found that there was a layer of poorer-quality clay in the foundation ground that lead those involved to believe that the worst slip surfaces would tend to develop along this layer.

The following figures 6 and 7 show the safety factors and the slip surfaces that were deduced from the calculations assuming surfaces that were respectively circular and flat.

As can be seen, there is a major difference in the value of the safety factor obtained.

It is believed that the surface that must be sought, through calculation, in the analysis of the overall stability ultimate limit state, is the surface that yields the lowest safety factor value regardless of its geometrical shape (circular, flat or combined).

Special attention is paid to cohesive ground or weak layers through which the slip surface tends to develop in flat form, but these surfaces would not be obtained if we only sought circular failure lines.

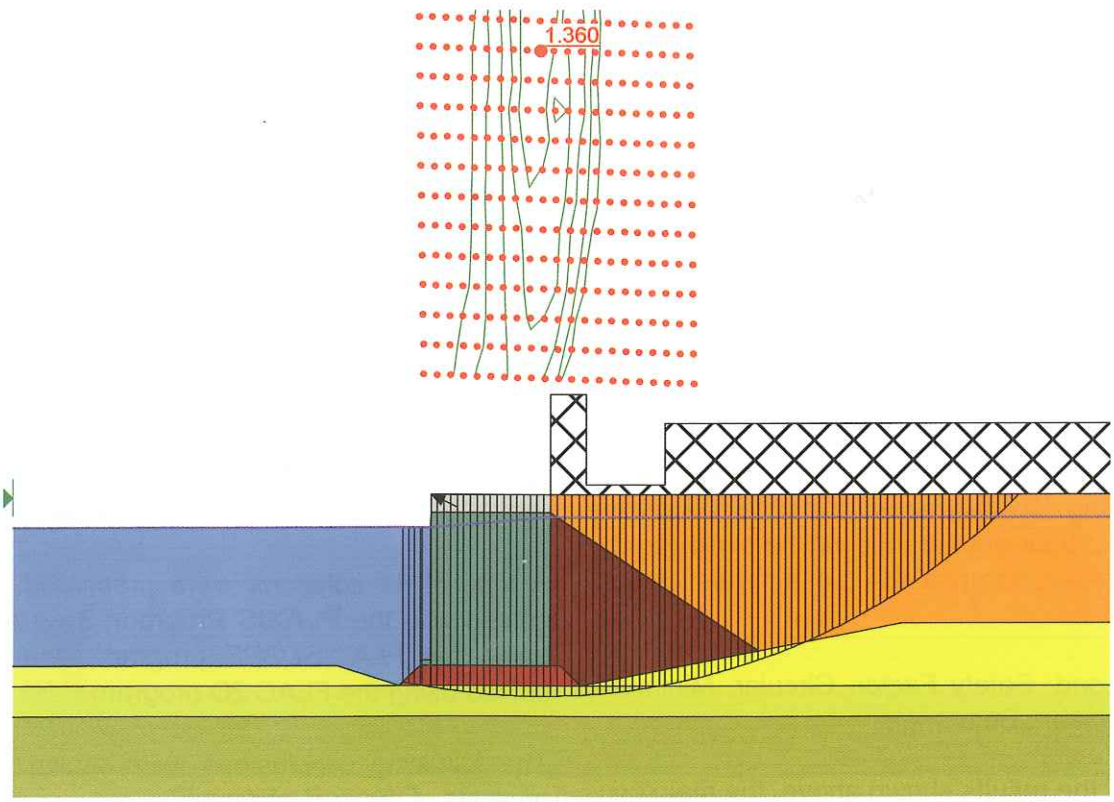

Figure 6: SF = 1.360

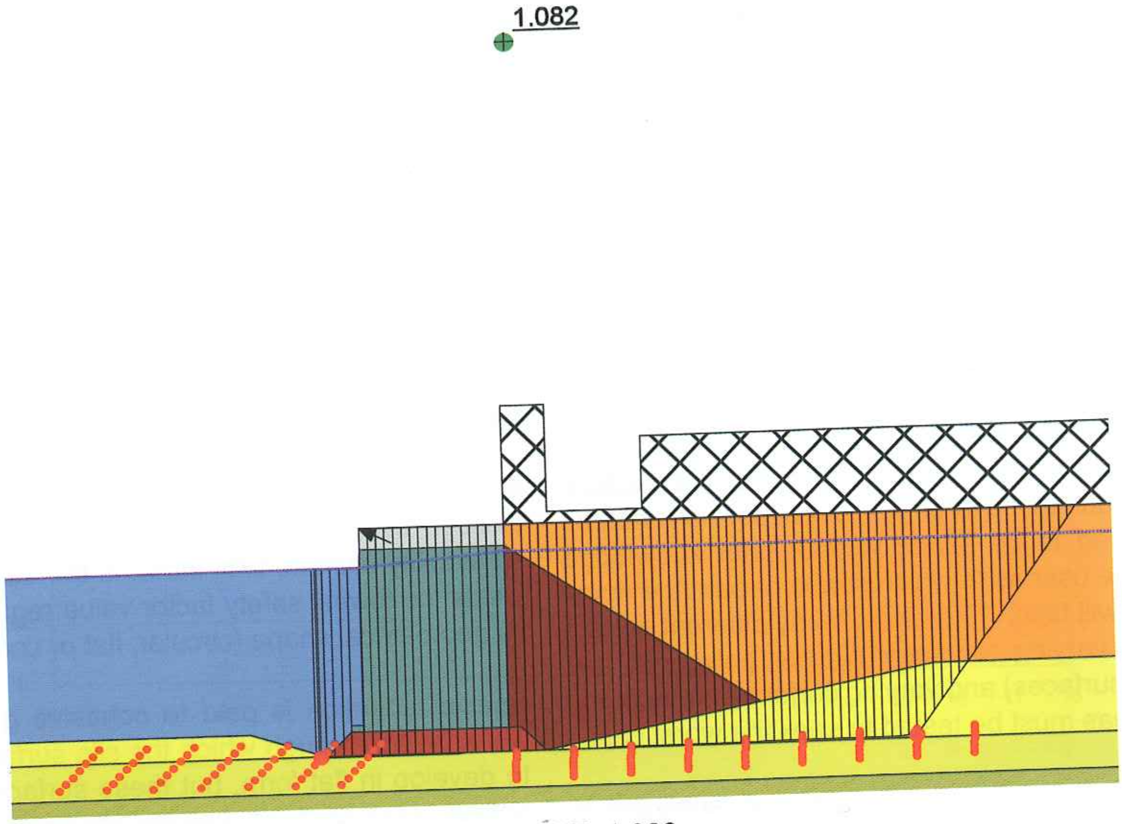

Figure 7: SF=1.082

5.3.3.2 Sinking and Plastic Overturning

If we analyse the sinking and the plastic overturning modes of failure, we find that in most cases the solutions are affected by convergence problems due to the changing sign of the angle that forms between the failure line and the horizontal, and the steeply sloping nature of the load. Therefore, it is advisable to fix the entrance angle, active, and the exit angle, passive, in such a way that the solution obtained for the problem is reliable, reducing the convergence problems to a minimum.

The criterion for fixing these angles will be those with which the minimum safety coefficient is obtained. It will be established that the failure lines begin at the bottom of the rear end of the equivalent footing. The surfaces thus obtained will be mixed, and their appearance will be similar to the theoretical appearance for these types of limit states.

Vertical Load, Safety Factor, Circular, Minimum, Brinch-Hansen, Beta angle

In view of the results shown above, the main conclusion that can be reached from the case being analysed is that there is a need to make calculations varying the slip surface exit and entrance angles, in order to make sure that the safety factor yielded is the smallest one. As a corollary to the aforementioned conclusion, it follows that the use of circular surfaces should be avoided when making this type of calculation.

The shape of the slip surface is associated with the chosen calculation method, because the latter has to be able to calculate any failure lines. Therefore, it is advisable that these be complete methods that comply with all the static equations. The Spencer and Morgenstern-Price Methods comply with both characteristic.

5.4 Comparative study of numerical methods

A total of 11 solutions were presented: 6 were solved with the PLAXIS Program; 3 were solved using the FLAC/SLOPE program; and 2 were solved using the FLAC 2D program.

The following conclusions were drawn from an analysis of these reports:

5.4.1 The respective safety coefficients obtained using the Limit Equilibrium Method

There is a certain trend leaning towards the safety factors (SF) being lower with Limit Equilibrium (LE) methods. The following potential explanations were given.

- The user did not predefine the worst failures in the Limit Equilibrium (LE) methods that were found using the numerical methods.
- The minimum Safety Factor (SF) found does not strictly conform to an overall stability failure mode, but it might be the result of an interaction between different mechanisms (for example, a combination of sinking and plastic overturning).
- The different calculation methodologies may give rise to different Safety Factor values for one single failure.

5.4.2 The grid

When the sensitivity of the results to the size of the grid elements was analysed, the following phenomena were detected:

- When the grid is made finer the Safety Factor decreases. For overall stability, variations of up to 15 % were observed between a coarse grid and a fine one.
- The situation is more critical in the case of long-term sinking (frictional materials), where variations of up to 70% were detected in the safety coefficient taken as an increase of the load exerted, as is shown by the red line in the following figure (taken from studies conducted with the PLAXIS Program):

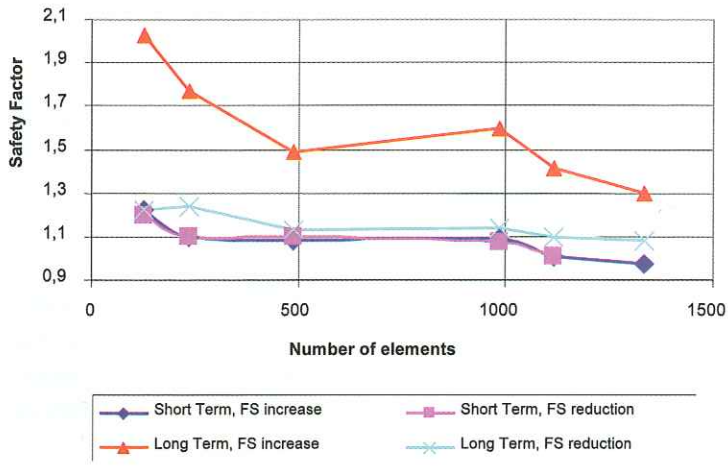

Figure 9

- The convergence problems increased when the grid was made finer.

o In the case of the problems solved with FLAC/SLOPE:

- It is not clear which of the different potential types of grid it is best to use. It would appear that the results converge to one single value when the grid is made coarser.

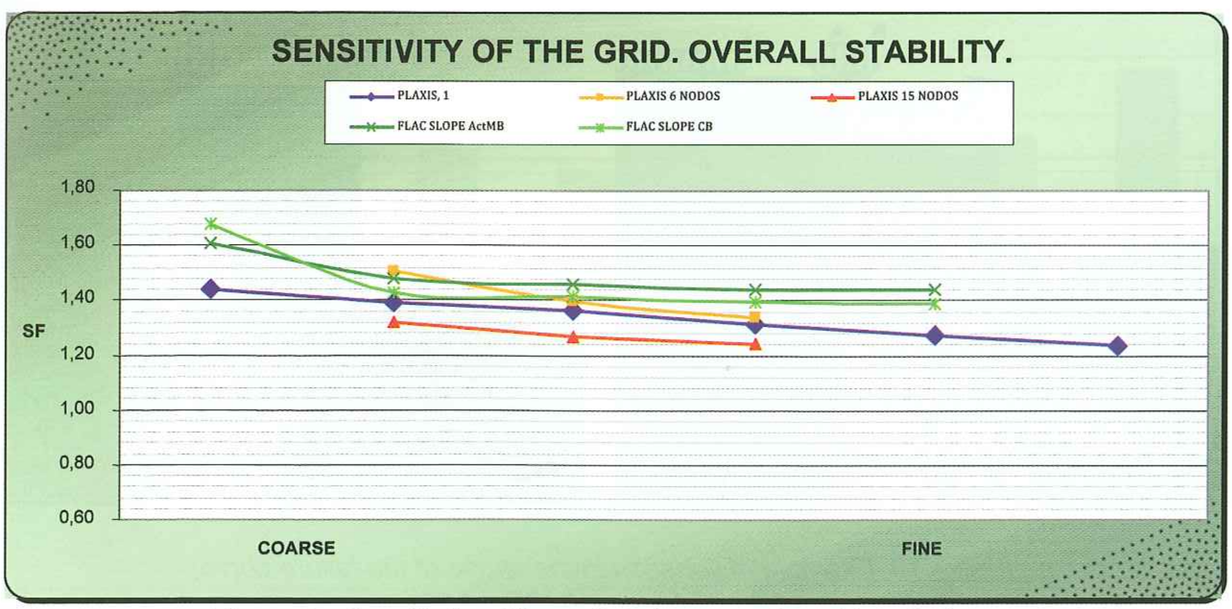

Figure 8: Sensitivity of the safety factor to the grid variations in the overall stability problem (long term)

- If there are no vertical slopes, the 'expanded, conform to material boundaries' type gives less convergence problems than other types that also conform to the geometrical boundaries of the problem.

o In the case of the problems solved with PLAXIS:

- Great sensitivity to the number of nodes per element (with variations of around 20 %, as can be seen when comparing the red and orange curves in the two preceding figures). In general, it is recommended that larger elements be used when studying limit state failure conditions, because it is accepted that they lead to more exact solutions, as can be seen in References 10 and 11 in the bibliography.

5.4.3 Dilatancy

The following facts can be observed when analysing the sensitivity of the results to the variations in the ground dilatancy:

- The numerical results are not very sensitive: safety factor variations are generally less than 10 % when the dilatancy is increased until it is equivalent to the angle of internal friction. However, there is a significant increase in anomalous results when the dilatancy value is very high.
- Although the SF only varies slightly, the failure shape can change considerably. A greater in-depth analysis of this fact must be conducted in the future.
- To be on the safe side, it is recommended that zero dilatancy be taken.

5.4.4 Comparison between sinking calculation methods

As can be seen in the following figures, which show the safety coefficients obtained by this failure mode in the cases proposed, these are well below the minimum coefficients set by the Maritime Works recommendations.

However, this does not happen when the overall stability is analysed for the same problem. The summary of the results obtained is shown in figure 12 on the next page.

In view of all this, we are of the opinion that one should go more deeply into defining the coefficients that are associated with each method (less for the numerical methods), because the sample of data obtained in this work is insufficient to make it possible to define general criteria.

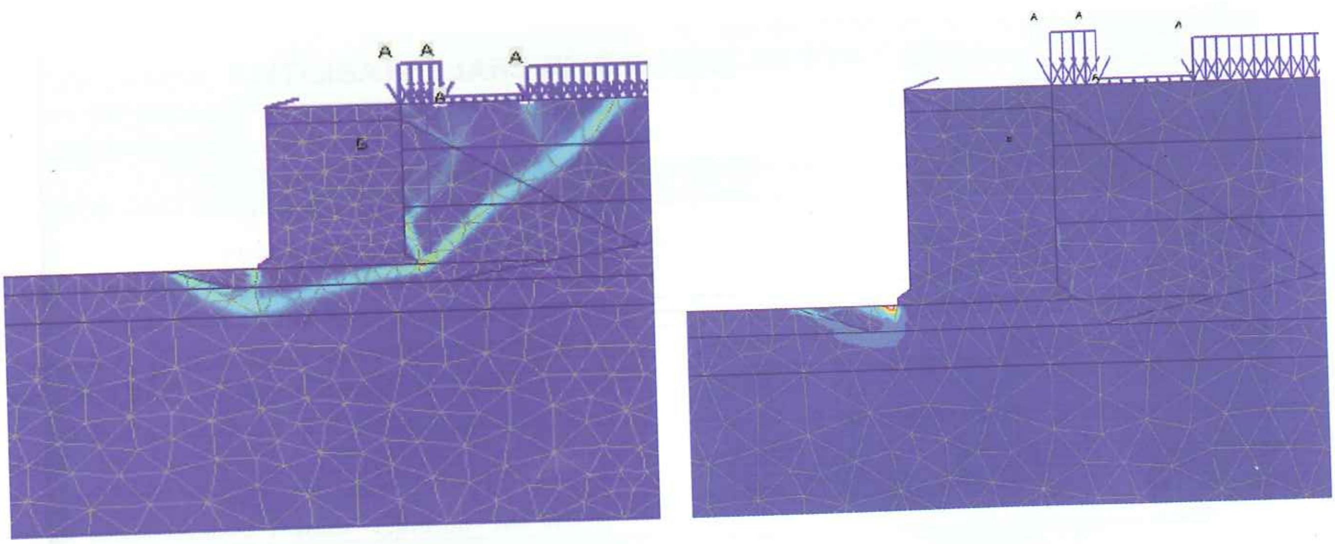

Figure 10: Example of variation in the shape of the failure curve, when dilatancy = 0 (SF = 1.28), and when dilatancy = Φ(SF = 1.35)

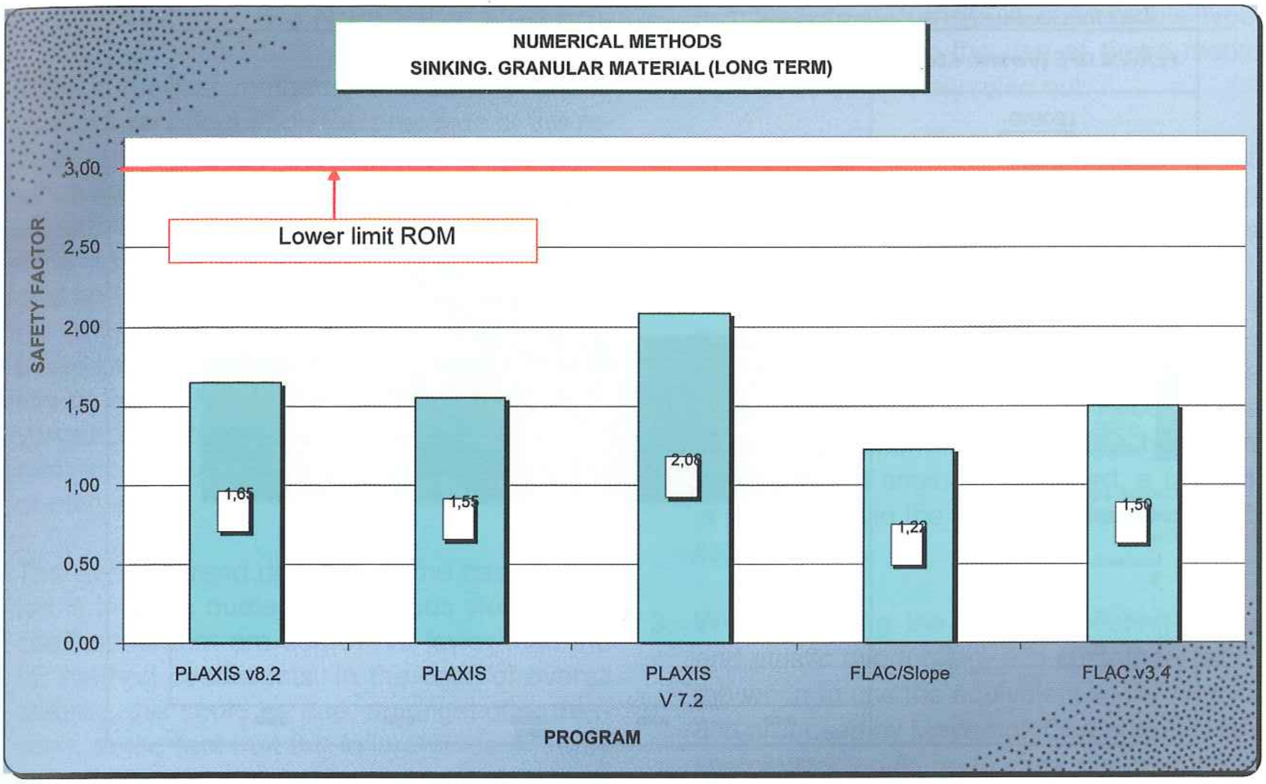

Figure 11: SF for long term sinking in granular material. SF understood as the amplifying coefficient applied to the actions for which the SF in the overall stability analysis yields 1. Minimum SF required by the Maritime Works recommendations is 3.00.

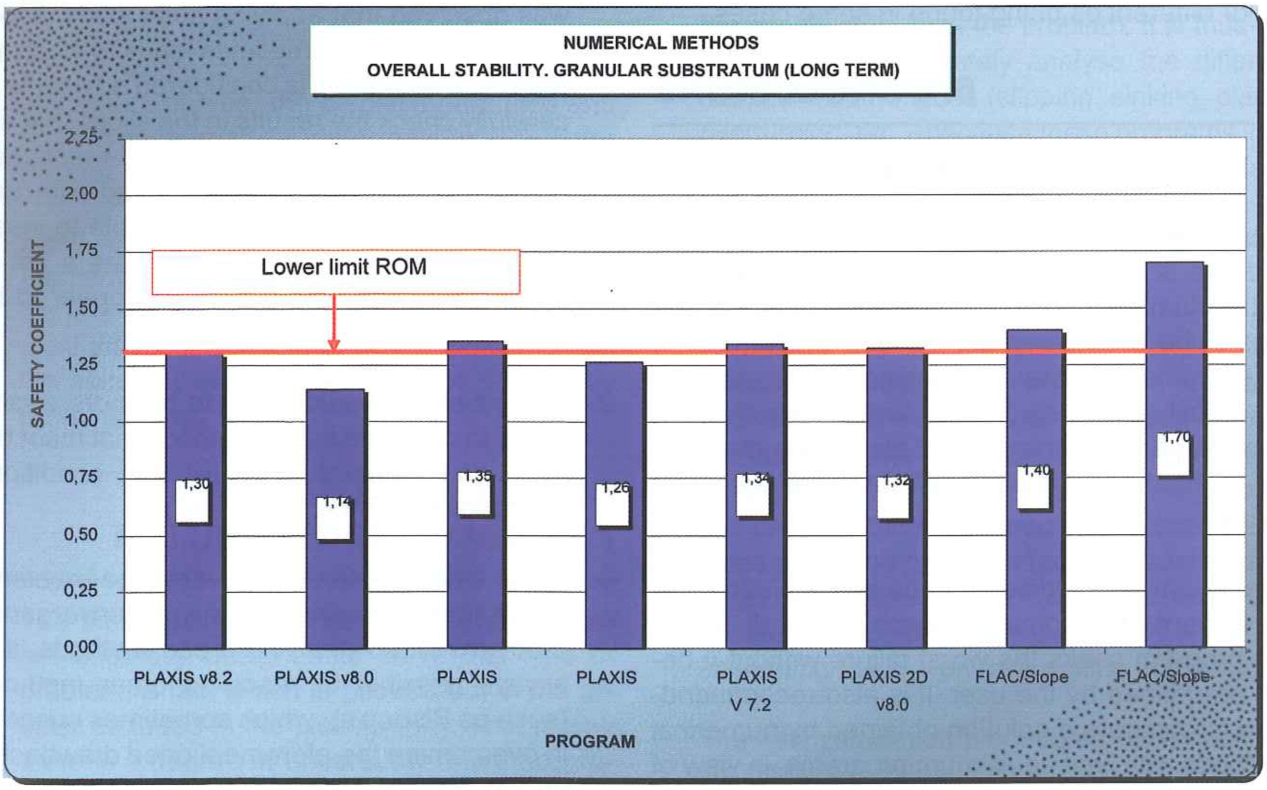

Figure 12: SF for overall stability in the long term. Minimum SF required by the Maritime Works recommendations = 1.3-1.4

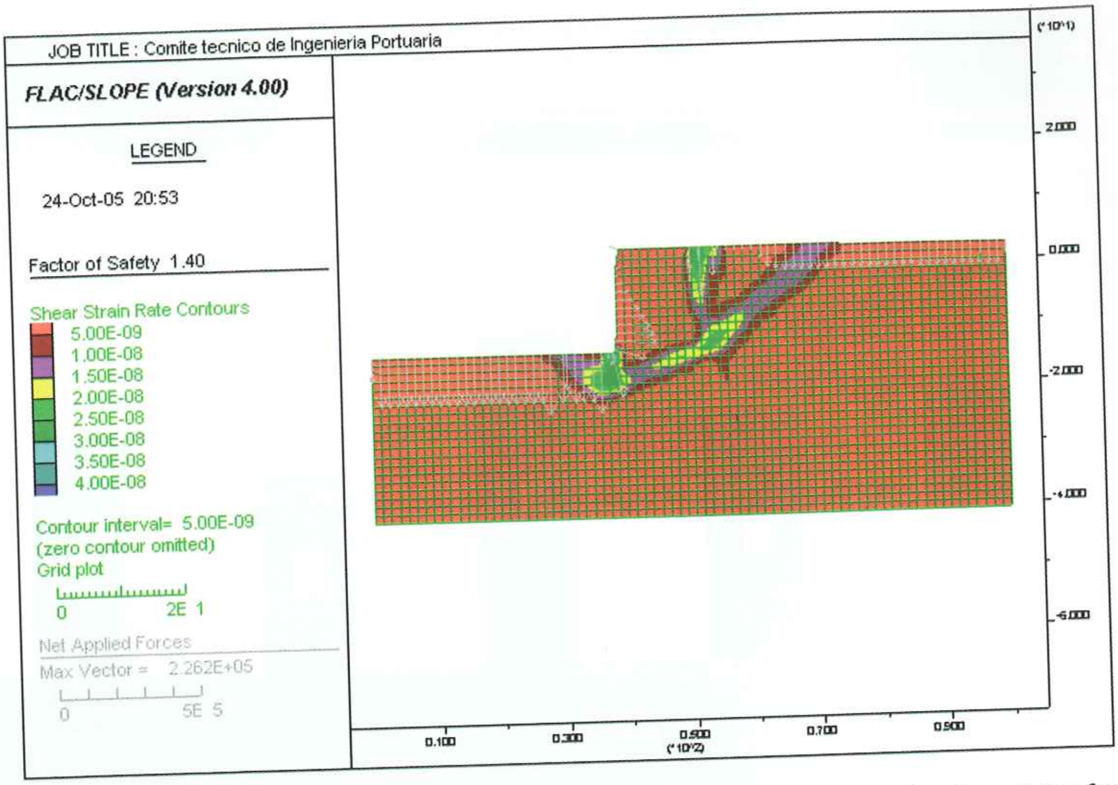

Figure13: Mixture of failure modes (overall with sinking/plastic overturning at the foot)

The results achieved with Numerical Methods, generally yield lower safety coefficients than the ones obtained using the Limit Equilibrium Method, major differences being found in some cases.

6. CONCLUSIONS

6.1 General Conclusions

The worst failure shape must invariably be sought, and this is not necessarily circular. For the Limit Equilibrium Methods (LE), where the potential failures to be considered are defined by the user, it is recommended that flat, polygonal, circular and mixed failures be studied, as well as different entrance and exit angles, etc. This means that with the LE methods it is often difficult to find the worst failure.

That is why it would seem to be advisable to compare them with some numerical method, where the program seeks the worst failure without it being predefined by the user. It is also recommendable to compare a solution obtained by numerical methods with limit equilibrium programs, in view of the fact that up to the present time the latter have been checked and contrasted on many more occasions than the former.

6.2 Limit Equilibrium Methods

1. In the Sinking and Plastic Overturning Study, it was observed that applying point loads, especially at the ends, sometimes leads to incorrect results. Therefore, it is considered advisable to carefully check the results in the slices that are affected by point loads. The above-mentioned anomalies have not been detected with uniform overburdens, so if it is possible to insert the action in this way, instead of as a set of equidistant point loads, it would appear to be more advisable to do so.

2. In principle, it would seem to be more appropriate to calculate using methods that meet the force and momentum equilibrium conditions (Morgenstern-Price, Spencer).

3. In the face of potential convergence problems or solutions involving zones with convergence problems when applying these methods, it is always possible to resort to other methods (such as Bishop's), which sometimes succeed in overcoming the aforementioned drawbacks, and to use such methods as auxiliary tools to make the solution fit, as long as their limitations are fully understood.

6.3 Numerical Methods

1. With numerical methods, the density of the grid has an effect upon the precision of the results: the safety factor (SF) tends to decrease when the grid density is increased. In the overall stability cases studied, variations of up to 15% have been observed between a coarse grid and a fine grid.

2. It has been observed that the greater the density of the grid the greater the number of convergence problems (this could be a problem of numerical instability on increasing the number of elements).

3. The general trend detected in the cases studied is that the numerical methods yield safety coefficients that are somewhat lower than the LE method coefficients. In the case of overall stability, this could be due, amongst other reasons, to the fact that the failure mode not only includes an overall failure, but also failure at the foot due to sinking and plastic overturning.

4. Particular care must be taken when studying the sinking or plastic overturning, because numerical instability can lead to incorrect estimations of the safety coefficients. Therefore, it is advisable to closely observe the load-displacement curves, the displacement field and the increase in shear deformations (the latter give an idea of the failure surface).

5. If the results obtained from applying the finite elements models are to reach optimum quality, it is essential to ensure that the geotechnical inspection provides all the data and that the accuracy of this information be sufficiently demonstrated.

7. UNSOLVED QUESTIONS FUTURE WORK CHANNELS

1. The limit equilibrium method programs were not originally designed to solve this type of problem, a fact which is pointed out in the articles included in the bibliography. That is why there is a degree of uncertainty and inaccuracy when they are used to calculate the safety factor for sinking and plastic overturning (See Reference 1 in the bibliography), which makes it difficult to use them in solving this type of problem. However, the use of these methods cannot be completely ruled out.

2. Although the limit equilibrium methods have certain advantages over other calculation procedures (experience, simplicity, rapidity, fewer geotechnical parameters, etc.), they must be used taking whatever precautions might be necessary to try and obtain the most accurate result in each particular case. Vertical slopes and sudden changes in the vertical forces between slices are elements for which this type of program was not originally designed, a fact which is pointed out in the articles included in the bibliography.

3. When studying the ultimate bearing capacity and plastic overturning, it is customary all over the world to use the equivalent width simplification proposed by Meyerhof. One potential future line of work would be to carry out research into whether this is the best possible simplification or whether it is better to develop other types of hypotheses.

4. Numerical methods enable the user to study the overall stability of the problem. It is thus unnecessary to separately analyse the different habitual failure modes (slipping, sinking, plastic overturning, etc.), because these programs indicate the least favourable failure. This would lead to a new approach to studying harbour caisson foundation studies (with their respective safety coefficients).

5. At present, it is customary to use analytical calculation procedures, limit equilibrium programs and numerical models when studying harbour foundations. The latter are becoming increasingly used for this purpose, because they enable the user to study with greater precision some types of ground problems (pore pressure variations, deformations, etc.). There are still uncertainties surrounding their use, but it would be interesting to carry on researching in this area.

6. The new calculation procedures (limit equilibrium programs, numerical models) have created an uncertainty about whether or not to keep on using the safety coefficients that were habitually thought of for analytical methods.

8. MEMBERS OF THE TASK FORCE

Under the direction of Eloy Pita Olalla (epita@increa.eu), the members of the task force (belonging to the Engineering Technical Committee of the Spanish Section of the International Navigation Association) are co-authors of this work and are noted as below:

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SUMMARY

In 2005, the Port Engineering Technical Committee of the Spanish Section of the Ports and Coasts Technical Association established a Task Force with a view to comparing the different commercial programs for calculating the stability of two-dimensional structures such as wharfs by limit equilibrium and numerical methods. This was done by solving a practical case of a wharf checking the different geotechnical failure modes (sliding, sinking, and overall stability) using limit equilibrium and numerical methods. The article analyses the differences obtained in some of the cases studied, stressing the advantages and drawbacks of each one of the methods used. Finally, ways of working in the future are established.

RÉSUMÉ

En 2005, le comité technique d'ingénierie portuaire de l'association technique ports et littoral (section espagnole de l'AIPCN) a mis en place un groupe de travail en vue de comparer les différents logiciels du commerce pour le calcul de la stabilité de structures bidimensionnelles telles que les appontements par des méthodes aux équilibres limites ainsi que par des méthodes numériques. Ce travail a été fait en étudiant le cas pratique d'un quai en vérifiant les différents modes de rupture géotechniques (glissement plan, poinçonnement, stabilité générale) par des méthodes aux équilibres limites ainsi que par des méthodes numériques. Cet article analyse les différences obtenues pour certains des cas étudiés et se concentre sur les avantages et les inconvénients de chacune des méthodes utilisées. Enfin, des perspectives de travail sont proposées.

ZUSAMMENFASSUNG

Im Jahr 2005 hat das Port Engineering Technical Committee der spanischen Abteilung der Ports and Coasts Technical Association eine Projektgruppe eingerichtet mit dem Ziel eines Vergleichs der verschiedenen handelsüblichen Programme zur Berechnung der Stabilität zweidimensionaler Konstruktionen, wie z. B. Kaianlagen, unter Anwendung von Gleichgewichtsbedingungen und mit numerischen Methoden. Dies erfolgte durch Lösung eines praktischen Falls eines Kais, indem die verschiedenen Arten des geotechnischen Versagens (Rutschen, Senkung und Gesamtstabilität) unter Anwendung von Gleichgewichtsbedingungen und numerischer Methoden überprüft wurden. Der Artikel analysiert die Unterschiede, die sich in einigen der untersuchten Fälle ergeben haben und hebt für jede der verwendeten Methoden die Vor- und Nachteile hervor.