ISSMGE TC 218

E-MEETING JULY 2019

Serviceability Limit States Analyses of Reinforced Soil Walls (aka MSE walls)

SUMMARY OF DISCUSSION

E-meeting started on Monday 8 July 2019 and ended on Sunday21 July 2019

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Topic under discussion: "ServiceabilityLimit States Analyses of Reinforced Soil Walls (aka MSE walls)".

Participation: 20 Experts from 5 Continents.

Introduction

EuroCode 7 (EN 1997-1, 2004) and other norms require the evaluation of displacements and settlements in Serviceability Limit States (SLS) conditions: the structure must meet all the requirements to ensure the required performance consistent with the intended use of the work itself in terms of deformations and displacements, both in static and seismic conditions.

Questions:

- Which are the SLS relevant to reinforced soil walls ?
- Is it possible to use numerical models (either FEM or FDM) to perform calculations of displacements and settlements ?
- Is it possible to use analytical methods (e.g. based on formulas) for displacement and settlements calculations ?
- Which reliability is afforded by numerical models and analytical methods when used for SLS analyses ?

SUMMARY OF DISCUSSION

1. Which are the SLS relevant to reinforced soil walls ?

The main SLS relevant to retaining walls in static conditionscan be considered to be:

a) local damage that can reduce the durability of the structure, its efficiency and/or its appearance;

b) displacements and deformations that may limit the use of the structure, its efficiency and/or its appearance;

c) displacements and deformations that can compromise the efficiency and/or the appearance of non- structural elements, plant, machinery;

d) vibrations that could compromise the use of the structure;

e) damage due to fatigue that may compromise durability;

f) excessive degradation of materials depending on the environment exposure;

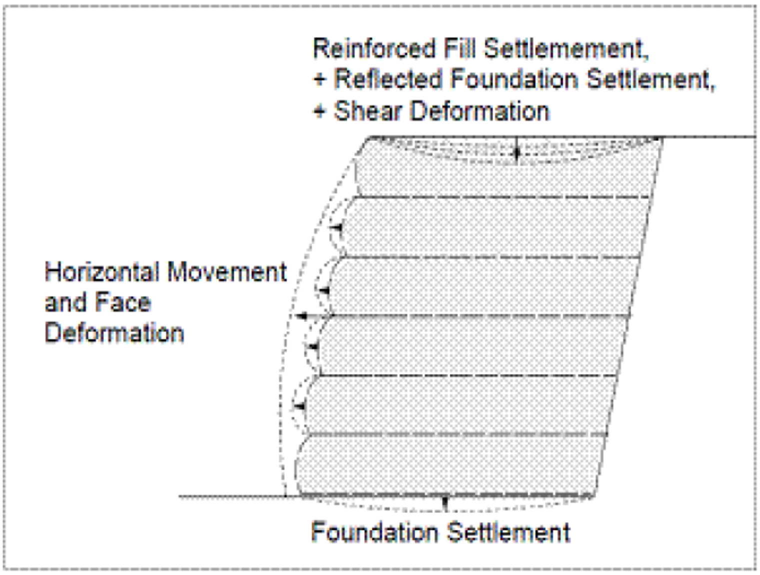
With regard to seismic actions, the SLS relevant to retaining walls can be considered to be:

g) Operational Limit Status (SLO): following the earthquake the construction as a whole, including the structural elements, the non-structural ones, the relevant equipment, must not suffer significant damage and interruption of use;

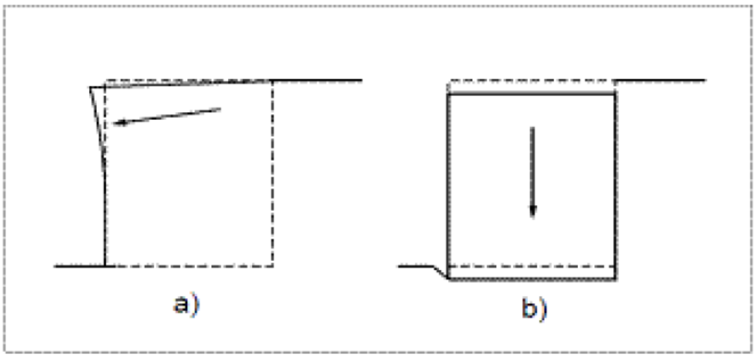
h) Damage Limit State (SLD): following the earthquake the construction as a whole, including the structural elements, the non-structural ones, the relevant equipment, suffers such damage as not to endanger users and not to compromise significantly the capacity of resistance and stiffness towards vertical actions and horizontal, remaining immediately usable even in the interruption of use of part of the equipment.

Reinforced soil works are ductile structures with high flexibility, which ensure adequate performance even in the presence of large displacements.

Indications on the SLS relevant to reinforced soil structures provided in Ebgeo and BS8006 are summarized in the following figures:



Sources of post-construction deformations in reinforced fill structures (from Ebgeo 2010)



Serviceability Limit States according to BS 8006 (2010): a) Wall deformation; b) Settlement

Hence, in case of reinforced soil structures the serviceability limit states can be reasonably limited to the following:

1) avoid excessive settlements at the base and at the top of the structure;

2) avoid excessive horizontal deformations of the face which may affect constructions in front of the structure.

It has to be noted that, in line with section §2.1(1) ofEC7, the above identified serviceability limit states can be addressed even by the adoption of prescriptive measures, as examples:

- Serviceability state 1) could be addressed by specifying that the reinforced soil structure shall be based on solid ground or rock, and that the granular fill is highly compacted to at least 95 % of standard Proctor density. Note that ASTM has 2 standards for compaction: one is Standard Proctor per D698 and the other is Modified Proctor per D1557. Use of the Modified Proctor basis within 1 m of the fascia can lead to significant horizontal deformation, even where 95 % is stipulated, while there is no similar issue with fill compacted below the base of the wall.
- Serviceability state 2) can be addressed by specifying that adequate Factors of Safety are achieved for the mechanism which may produce horizontal deformations, that is direct sliding along reinforcements, pullout of reinforcements, connections between reinforcements and face elements.

In any case, when other constructions do exist in close proximity of the face of the structure, more detailed analyses may be required.

The discussion on specific SLS follows.

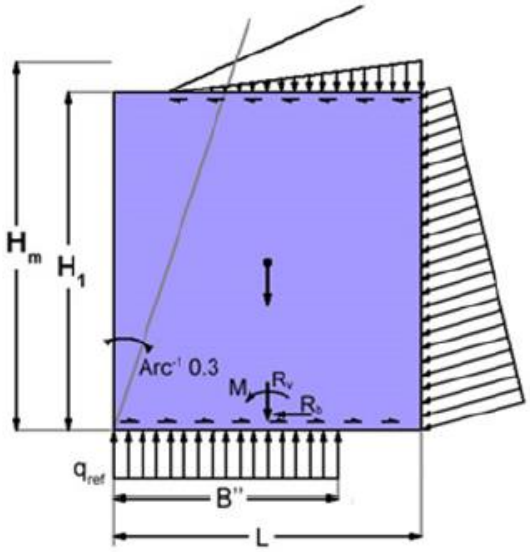
1.1 Foundation settlements

This SLS should be considered as part of the geotechnical analysis of the whole structure, and not be limited to the reinforced soil structure alone,whereit is just considered in its geometric and weight properties. In fact the critical aspect is the correct prediction of the behavior of the soil based on adequate geotechnical investigation of the site.

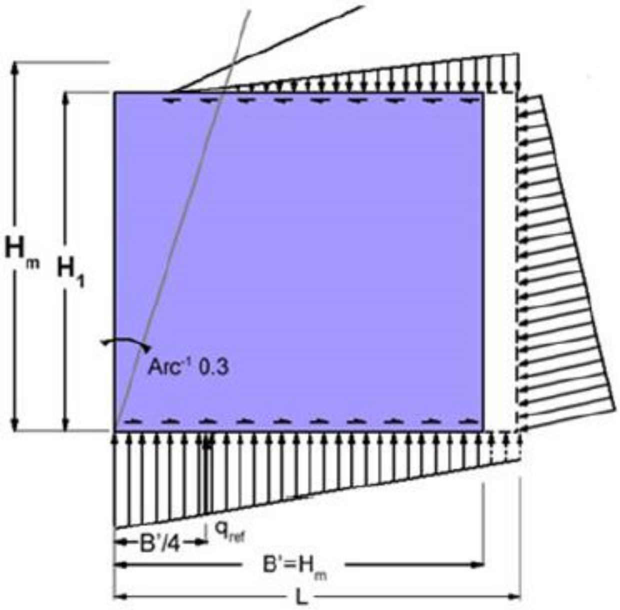
However, in reality settlements of the foundation occurs mainly during construction and it is difficult to calculate what is the residual settlement once the structure is built.

Differential settlement considerations are prominently addressed in AASHTO (Section 11.10.4) rather than settlements alone. Settlements are somewhat referenced in AASHTO by way of FHWA NHI-06-088, but these are with general respect to embankments as a pass through reference from FHWA NHI 10-024 on MSE walls.

The use of Meyerhof pressure distribution for MSE loading is one way to more accurately evaluate settlements if a detailed geotechnical evaluation of prevailing subsurface conditions has been performed. See the following figure.



$L<H_m$ Meyerhof Method



$L>H_m$ General Method

Where B'' = B' - 2 (M/R_v) and q = R_v/B''

A lot of confusion seems to exist between the engineers who needs to check the foundation settlements when a reinforced soil wall is designed. When the design of the Reinforced Soil Wall (RSW) is divided between the designer doing the internal stability and another designer doing the external stability, the analysis of the settlements sometimes is considered only until the end, without an adequate geotechnical investigation. But this should be part of the geotechnical analysis and not limited to the structure alone.

Possibly it should be avoided that an Engineer performs internal stability and another Engineer performs external and global stability. The reinforced soil wall is a structure by itself and a single Designer should be responsible for the whole structure and its interaction with other structures and surrounding soils (below and behind).

If more than one engineer is responsible for the stability of the structure (internal – external) still, there should be a sharing of information and design in order to ensure that the design interface is clear ad agreed by both parties. Surely having one engineer is by far easier and better.

1.2 Reinforced fill settlements

Reinforced fill settlementsare also important considerations, especially when the structure is used e.g. as directly loaded bridge abutment. However, the “intrinsic” settlements/deformation of a reinforced fill structure itself depends very much on the quality of construction, e.g. compaction degree. Depending on the sensitivity to deformation of the structure itself, one might consider to define certain compaction degrees and characteristic of the fill material itself, as for example not every fill material can be compacted to 103% standard Proctor density. This is another reason to recommend Standard Proctor based compaction effort since unintended consequences result when a high level of compaction is specified. This is counter intuitive in that Owners may believe they get better performance and less deformation when specifying a high degree of compaction.

Only limited “estimated values” are available in literature in relation to the wall height to get a rough idea of the magnitude of the “intrinsic” settlements/deformation.

Since SLS can be addressed also "by specification", this is the case for "intrinsic" settlements, which should be limited to occur during construction or within a well defined period after the end of construction.

In this case, aspecification based guideline may be more appropriate rather than methods for calculation in terms of SLS.

Design standards define adequate soil material and, based on them, compaction specification is applied.

However, more and more we are moving towards marginal fills with high fines content, creep, variation of soil properties with stress and time. These are particular cases which should be addressed on its own (residual soils is a well known headache) which requires knowledge of the soil behavior as well as of construction practice. The use of draining geosynthetics to reduce the pore water pressure is well-known and used, as well as compaction specifications. Maintaining joints in the fascia can supplement drainage as well. The bulging of segmental block walls has pointed to the issue of hydrostatic buildup when the block fit tightly together.

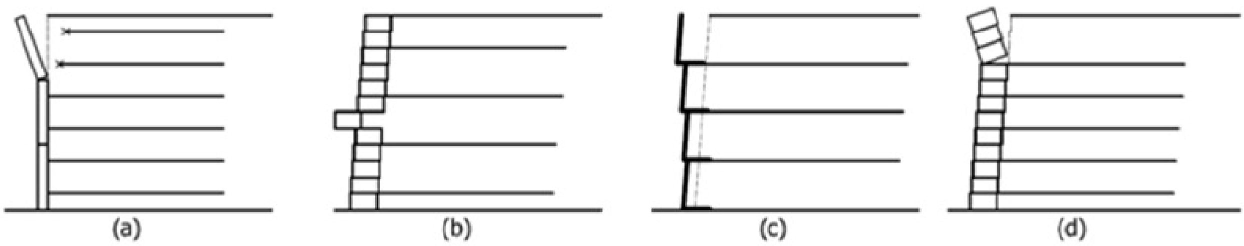
The use of marginal fills is a technical, economical, environmental requirement in many projects, and cannot be avoided; with these fills additional analyses and design for internal drainage, "intrinsic" settlements, and post construction deformations should be made mandatory.

1.3 Reflected foundation settlements at top,

Same considerations as for reinforced fill settlements apply.

1.4 Horizontal movements,shear deformationsand face deformations

Face deformation is a SLS for all types of reinforcement and facing system, since it can occur in many ways as shown in this figure:



Examples of limit states due to deformations of reinforced soil structures: (a) and (d) displacements by rotation of facing elements, (b) shear displacements between face elements (bulging), (c) shear displacements between face elements and reinforcements.

The situations in the figure can be viewed as both ULS (if they bring to failure) and SLS (if they bring to excessive deformations).

Face deformation is a function of the type of backfill used, the rigidity of the fascia, compaction and construction techniques used, joints in the fascia and drainage behind the fascia.

Unless the codes specifically require this elements (and others that influence this area of performance) it will be incredibly hard to address service limits based on a wide spectrum of conditions.

The matter of deflection is somewhat difficult to assess when aesthetic considerations come into play from the public.

Bulging due to deformation and stresses occurring within the reinforced mass should be considered. Where granular soils are used with geosynthetic or steel reinforcement and where design is to AASHTO/FHWA standards (North America), bulging of the overall mass is not commonlyobserved. For very high walls (but how high is that? > 12 meters? By experience greater than 10 meters is considered a high wall in this context), perhaps bulging can become more apparent, but there are very few observed walls built with granular soils and geosynthetic or steel reinforcement where a bulge can be seen.

For reinforced walls with higher fines content or poor quality soil, which would have lower elastic modulus when compacted, greater bulging might occur – and has been observed – sometimes leading to facing failures.

Greater bulging may also occur where flexible facing that can relax or strain after wall layers have been constructed (e.g., when completing the wall or after wall completion) provide less soil confinement, and can contribute to greater deformation of the face and greater strain of soil near the face. This can increase bulging particularly near the wall toe and within the stress concentration zone near the wall toe – which can then contribute to outward rotation of the wall, causing deformation higher up the wall and behind the reinforced zone.

Regarding bulging of facingmaterial, flexible facings can lead to less soil confinement, but also different aesthetics. The project owner’s tolerance for different aesthetics should be considered in selecting the facing material and potential deformation of the facing layers that could be observed. Precast concrete fascia deforms less than gabions or wrapped faces. Whether this is acceptable or not may be a project-based decision – but should be considered and accounted for in selecting wall reinforcement and fascia type.

On the other hand, backfill and corresponding drainage, facing and reinforcement plays the main role in bulging. A very stiff face (concrete panel or welded mesh) can easily bulge if the backfill is not correct, since the consolidation of the backfill generates horizontal pressures on the face as well as internal settlements which can displace the face. While a flexible face is able to better accommodate such displacements, thus “hiding” the problem.

Bulging and settlement are relevant matters to address on service limits. However, bulging will need to be considered with respect to facing material. Certainly, wire facing can be subjected to more bulging than large precast panel facings. Anyway it could be argued that discrete segmental blocks could also respond to greater bulging than large precast panels, but less than wire facing. Then, there are full height precast panels that are even more rigid and less adaptable to bulging.

Hence bulging should be considered in different ways depending on the facing material. Adding a range of limits depending on the type of facing could help in the design and construction for Reinforced Soil Walls.

For walls with flexible facings (wire facing/vegetated facing, wrapped face, etc) there is a growing use of soils with high fines content, poor soils and marginal soils, to reduce costs, but mainly to reduce carbon footprint. With fines soils and marginal soils, bulging is a big issue, during construction and post-construction, and limits set in the norms could help with the construction and the performance of the RSW. However there is not yetconsensus on the specific values for the bulging limits.

Regarding the use of marginal fill, one can think about the possibility to improve the material properties for a certain area in the front.

Furthermore bulging can also be a problem of product installation knowledge as several system requires an initial movement of the facing, which should be taken into account during construction, whilemany times this is not applied, becoming a bulging afterwards.

In some countries, we do observe the tendency to increase the layer distance. If the distance between the single reinforcement layers becomes too great, there might be zones in between those layers, where the soil is not anymore beneficially influenced by the reinforcement layers. As a result deformation at the front might occur. Depending on the fill material and reinforcement type used, a zone of influence can be observed of up to 30 cm, which would lead to a “logic” layer distance between two reinforcement elements of 60 cm.

In case of large vertical spacing of reinforcements, it is important to analyze the stability of the structure first, but then to analyze also the stability of the face and the displacements / bulging; there are many examples of "hybrid" structures with primary reinforcement at large vertical spacing designed to provide stability in ULS, and with secondary reinforcement at smaller vertical spacing designed to afford the stability of the face and the displacements / bulging; for sure with a single type of reinforcement at large vertical spacing both local stability at face and SLS analyses would be difficult to be verified.

The spacing of the reinforcement needs to be designed in line with the face, as spacing of more than 2m has been used but it was supported by local reinforcement in a steep slope or in vertical application by a facing which could withstand such horizontal pressures. Shorter length intermediate reinforcements near the wall face can be used to arrest bulging where main reinforcement connected to the fascia is widely spaced.

1.5 Excessive elongation of reinforcement at short-term and long-term

Elongation of reinforcements are relevant to geosynthetics only, while steel reinforcements would have tensile limits instead of elongation considerations.In fact for reinforcement with a high cross section modulus (such as bar mats and steel strips) excessive elongation of reinforcement is not a concern.

Elongation may be a concern only for (current) geosynthetics and this may be limited using a strain based approach instead of the commonly used rupture approach. If codes were to require for geosynthetics a strain based approach service limits may be easier to predict.

Anyway practice and experience have shown that deformation associated with geosynthetic elongationis not a real concern that affects performance for geosynthetic-reinforced MSE walls designed to current standards (e.g., like AASHTO/FHWA). Moreover, the potential for excessive deformation due to elongation is addressed through the design procedures and application of creep reduction factors. In fact it was never observed that in walls properly designed and constructed geosynthetic elongation controlled the material selection or wall performance.

Geosynthetics used for soil reinforcement adhere to strength criteria and strain criteria in line with general practice, therefore already using Reduction Factors (ULS) we are actually verifying also SLS conditions. Furthermore it is well known that current design methods for Gesoynthetic reinforcement highly overpredicts the tensile forces (Bathurst, 2018), which is a further constrain applied to ULS, which results in very small tensile forces in the reinforcement, thus low creep strain.

We do consider this fact by applying the Reduction Factor for creep within the design procedure. For critical structures one might add an additional check on the elongation compatibility, but in general this step is not necessary.

Using marginal fills, the overall deformation behavior needs special attention and a long-term strain limitation for the geosynthetic reinforcement might be one of the measures to be taken, that is when using fine/poor soils, there should be a service limit for elongation.

A specific step in the design procedures may be added to include a service limit for elongation, so that the importance of this factor is not forgotten as design procedures continue to advance and become potentially less conservative for geosynthetic reinforcement.

But we may have a few more decades to wait to see where the creep and stress relaxation of geosynthetics leads us.

Current design standards that result in geosynthetic strains down near or below 1% may be overly conservative and therefore, by default, but not by intentional action in the design process, geosynthetic elongation is not contributing to excessive deformation.

For geosynthetic reinforcement, some standards already provide indications that the post-construction creep strains should not exceed 1 %, but this should be just a preliminary indication in case that Serviceability Limit State analyses are not performed.

In fact the post-construction strains in the geosynthetic reinforcement depend on the tensile strength mobilized in each point of the reinforcement, while the post-construction horizontal deformations of the wall depend on the average value of the post-construction creep strains in the reinforcement.

Therefore, in any case, the 1 % post-construction creep strains in the geosynthetic reinforcement shall be intended as the average value along the whole reinforcement length.

BS8006:2016 includes the following table:

Table 19 **Serviceability limits on post-construction internal strains for bridge abutments and retaining walls**

Structure	Strain %
Bridge abutments and retaining walls with permanent structural loading	0.5
Retaining walls, with no applied structural loading i.e. transient live loadings only	1.0

This table can only be interpreted as that the post construction internal strains limit shall be applied to the reinforced soil structure, and not to the single reinforcement layer, as it is logical.

This can be considered as a normative limit to post construction horizontal displacements, that is a limit on a SLS.

As example, if a reinforced soil bridge abutment is designed with 10 m long geogrids, the SLS limit on post construction horizontal displacement **of the structure** would be:

max horizontal displacement = 10 m x 0.5 % = 50 mm

Moreover BS8006:2016 at clause 5.3.3.3 requires that: *"The average serviceability limit state design load, T_{avj}, should be calculated to ensure that $T_{avj} \leq T_D$ at all times in the design life."*

Given that design is usually performed using the Design Strength T_D, where the Reduction Factor for creep at 120 years have already been applied, the post construction creep strains do not affect the stability of the walls in Ultimate Limit State conditions, but can only produce horizontal displacement at the face which can affect only the Serviceability Limit State conditions.

The analysis of post-construction horizontal displacement should prove that even the Serviceability Limit State conditions (including the above derived limit on post construction horizontal displacement) are verified.

2. Is it possible to use numerical models (either FEM or FDM) to perform calculations of displacements and settlements ?

It is possible to use numerical models (either FEM or FDM) to perform calculations of displacements and settlements, but the model needs to be thoroughly calibrated and validated to avoid macro errors. In particular the interface between reinforcement and soil has to be carefully characterized both for pullout and direct shear, based on the pullout factor f_{po} and the direct shear factor f_{ds}, or equivalent parameters. Moreover the dilatancy angle along the interface has to be properly calibrated.

FEM or FDM models require validation by comparison with a known, monitored structure, and finally require a not easy critical judgement of results. In fact it is common experience with numerical models that a small variation just in one parameter brings to inconsistent results. Removing the inconsistencies of numerical models is always a difficult exercise.

FEM calculations have been performed in the USA on reinforced soil structures as the 43 m tall SeaTac 3rd Runway MSE walls in Washington state. Such modelling (Flac and Plaxis) was done before and after the walls were built with comparisons to extensive field exploration and instrumentation. Calibration of models is extremely important and must have foreknowledge of the material components of the MSE wall including fascia type, panel connections, reinforcement type (steel or geosynthetic), reinforcement geometry (strips, grids or sheets), bearing pads between fascia (if it exists), backfill properties and load conditions (including seismic). The models developed for SeaTac slightly overpredicted settlements and lateral displacements. Technical papers addressing SeaTac are readily available on-line.

Models are particularly sensitive to assignment of Elastic Modulus values, and in the case of backfill, the assignment of Poisson's Ratio and Coefficient of Friction.

Calibration is an issue. Considering that most of the instrumented structures used for calibration are special cases or projects were new/uncommon circumstances are in use (reason why they were instrumented) the validity of the calibration may not be the most accurate for general FEM or FDM models.

FEM calculations are possible to use to predict displacements and settlements, however they strongly rely on calibration. On many projects numerical models have been used with all the geotechnical parameters based only on correlations, without proper calibration. The results have been used only to tick a box on the requirements of the project, but not to do a real analysis of the performance of the structures. Howeverin other cases numerical models have been used to help to improve designs and make decisions based on the predictions for different scenarios of the soil conditions.

The use of FEM model is highly dependent on the input parameters of the soil (not much of the reinforcement, asthey are known). However in most cases we barely know the friction angle of the material and the model is calibrated on general assumption from the type of material as well as an iterative process to assess the deformation based on experience. Unless a thorough geotechnical investigation of the backfill is done, FEM models are just a black box. Interestingly enough, we should look at guiding the designer on what value to use (general) or what test to undertake to extrapolate such input parameters.

Hence, FEM can help to get an “orientation” in regard to the magnitude of expected deformation. But to have a really reliable numerical model, one has to take into account all relevant construction steps, and a sufficient validation and calibration of the model has to be done. Many timesone can observe that a numerical model has been “fit” to one(!) specific situations, but it does not work for the construction before or after. The much bigger benefit one can get from numerical investigation of a structure is to gain a better understanding of the load transfer and to identify the “critical” areas, at least for complex structures, while for the standard structures this might not be necessary.

3. Is it possible to use analytical methods (e.g. based on formulas) for displacement and settlements calculations ?

The common practice is to use numerical models (either FEM or FDM) to perform calculations of displacements and settlements, but in this way all the advantage of LEM (simple and realistic models, easy to understand and correct) are lost.

In fact, LEM models, even for displacement calculations, are robust and easy to adjust, in case that some evident inconsistencies appear in results.

Few papers have been published on analytical methods for displacement of reinforced soil walls; anyway these few papers show, by comparison with the measured data on instrumented structures, that the proposed methods afford realistic value of horizontal displacements.

Two of these methods, based on different approaches, yet affording similar results, have been published in the following papers:

Dobie, M.J.D., and McCombie, P.F. (2015). Serviceability limit state check in reinforced soil design. Proc. XVI ECSMGE Geotechnical Engineering for Infrastructure and Development. Edinburgh, UK.

Rimoldi, P. (2018). Horizontal displacements of reinforced soil walls from Limit Equilibrium calculations. Proc. 11ICG, 11th Int. Conf. on Geosynthetics. Seoul, Korea.

About settlements: traditional methods, like Schmertmann (based on CPT) and Burland – Burbridge (based on SPT), Terzaghi (based on oedometric consolidation), Janbu (for immediate settlement) can be satisfactorily used for reinforced soil structures.

Here is where the use of Meyerhof pressure distribution for MSE loading is a way to more accurately evaluate settlements when a detailed geotechnical evaluation of prevailing subsurface conditions has been combined with an understanding of loading by the MSE wall volume. Several technical papers that include the method are included in early papers addressing MSE walls by The Reinforced Earth Company (USA) and Terre Armee.

MSE walls and the fills they retain can result in large stress fields. MSE wall settlement may be evaluated treating the MSE wall as a footing or using techniques similar to retaining wall evaluation procedures first developed decades ago. Or rather, the entire MSE wall and retained fill should be modeled using programs that have the ability to consider the large mass, deep and wide stress field, and shape of the settlement profile both parallel and perpendicular to the wall face.This can be done with both relatively simple programs (as example: Settle3D, which incorporates traditional settlement and consolidation analyses techniques), and on occasion FEM/FDM analyses.

Settlement parallel to the wall face should be considered for the differential settlement impacts on fascia, which can affect fascia selection.

EN 14475(2006). Execution of special geotechnical works - Reinforced fill. Annex C provides typical limit values of differential settlement in wall materials for the most common configurations of reinforcement and fascia. The use of such indications would allow an intentional check of this service limit during the design process.

Total settlement and differential settlement perpendicular to the wall face are also considerations for designing drainage installed in or below the wall, reinforced slope, and retained fill.

The whole behavior always depends pretty much on the construction quality. In general, the prediction of settlement does work quite fine, whereas the prediction of horizontal deformation of soil is already quite difficult even without any reinforcement element. Empirical methods based on field observation are a good way to get an orientation regarding expected deformation. For sensitive structure one might use different approaches to estimate the expected deformation, such as a combination of field experiences, FEM and analytical or empirical methods.

4. Which reliability is afforded by numerical models and analytical methods when used for SLS analyses ?

The reliability of numerical models, when used for SLS analyses, is quite questionable without proper calibration and validation.

Analytical methods can be considered more robust, even when used for SLS analyses, yet their reliability has been verified only for the specific examples in related papers (like the two ones above reported).

In general the reliability of both numerical models and analytical methods, when used for SLS analyses, is still an open field of research; while there are many publications on reliability of reinforced soil structures in ULS conditions,it seems that there is a lack of publications on reliability of reinforced soil structures in SLS conditions.

Such reliability models may be possible for forensic analyses on in place walls, but in practice the designer rarely has all the components of information needed such as wall type, material physical characteristics information, detailed subsurface information and construction methodology. Code development for proposed structures by necessity has to be on the conservative side and models are a good source for evaluating complex structures in the context of standard code restrictions. However, the possibility of intentionally or unintentionally manipulating input values for models should be seriously considered before fully ascribing to the results.

It is important to consider what the purpose of conducting a numerical model of a reinforced structure would be and how critical the accuracy of the results need to be before deciding whether or not numerical modeling has application. Designers often are using the results (deformation, strains, reinforcement stresses) to make economic decisions. Knowing behavior and how close or far from a limit or service state the design, and subsequent construction, is can be valuable without needing to be really accurate or to spend lots of time with parameter calibration, testing, etc. Where overall strains in soil and reinforcement are low, and interaction between the materials shown to be high, it may not be necessary to model interface elements and slip surfaces.

Numerical modeling for MSE and reinforced slope applications can be used if uncertainties in the parameter selection are considered in the analyses.

It really depends on the application of the reinforced structure how accurate a prediction has to be. A simple example is the comparison between a noise barrier and a directly loaded bridge abutment. The more important deformation behavior becomes for the application the higher has to be the reliability of the models/methods. In certain projects also limit values have been predefined and then controlled by ongoing measurements.

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