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On the use of finite element models for geotechnical design

Ronald B.J. Brinkgreve, Mark Post

Abstract: The Finite Element Method is primarily meant for serviceability limit state (SLS) calculations, but it also offers possibilities for ultimate limit state (ULS) calculations in geotechnical design. The combined use of SLS and ULS calculations with partial safety factors according to the different design approaches in the Eurocode 7 can be time-consuming and prone to error. In this contribution a Design Approaches facility is presented for an efficient use of partial safety factors in a finite element environment. In addition to a description of the methods used in this facility, an example is elaborated involving the geotechnical design of an embedded sheet pile wall using different design approaches.

Kurzfassung: Die Finite Elemente Methode wird im Bereich der Geotechnik vorrangig für Nachweise im Grenzzustand der Gebrauchstauglichkeit (GZG) verwendet, sie bietet darüber hinaus jedoch auch Möglichkeiten zum Nachweis des Grenzzustandes der Tragfähigkeit (GZT). Die Kombination von GZG und GZT Berechnungen mit den Teilsicherheitsfaktoren der verschiedenen Nachweisverfahren des Eurocode 7 kann jedoch sehr zeitaufwändig und fehleranfällig sein. In diesem Beitrag wird ein Werkzeug zur effizienten Verwendung von Teilsicherheitsfaktoren im Rahmen der Finiten Elemente Methode vorgestellt. Die verwendeten Methoden werden erläutert und die Nachweisführung mit den verschiedenen Nachweisverfahren wird am Beispiel einer eingespannten Spundwand dargestellt.

1 Introduction

In the past decennia the Finite Element Method (FEM) has been used increasingly for the analysis of stress, deformation, structural forces, bearing capacity, stability and groundwater flow in geotechnical engineering applications. Besides developments related to the method itself (e.g. new constitutive models for soil and rock, new numerical procedures and calculation methods), the role of the FEM has evolved from a research tool into a daily engineering tool. The method has obtained a position next to conventional design methods, and offers significant advantages in complex situations.

Regarding the use of the FEM in geotechnical design, methods have been developed to deal with the requirements of design codes. For decades, the method of strength reduction was the way to evaluate global geotechnical safety factors. The introduction of Eurocode 7 inferred the need to incorporate partial factors for Actions, Materials and Resistances. Some of this is difficult to handle in the FEM, where actions and resistances from the soil are a result of the equilibrium solution rather than a priori input data. Alternatively, Eurocode 7 allows for partial factors on 'Action effects', which offers possibilities for the FEM.

Meanwhile, some authors have published examples of finite element calculations according to the different design approaches in Eurocode 7, with emphasis on the differences in results and the influence of the soil constitutive model being used (e.g. Schweiger, 2010). The purpose of the current contribution is to describe a Design Approaches facility for an efficient use of partial safety factors in a finite element environment. Chapter 2 describes how partial factors can be taken into account using the Design Approaches facility and how to deal with design calculations in relation to serviceability state calculations. Chapter 3 demonstrates an elaborated example of an embedded sheet pile wall. At the end of this contribution some conclusions are drawn.

2 The use of partial safety factors in FEM

Design codes primarily deal with ultimate limit state (ULS) design, i.e. stability issues, bearing capacity and failure, whereas the FEM is primarily used for stress and deformation analysis at given working load conditions. The latter is more closely related with serviceability limit state (SLS) design rather than ULS design. In urban projects and other situations where deformations are critical, SLS requirements are often considered in addition to ULS requirements. This has contributed to the increasing role of the FEM in geotechnical design in the last decades.

Performing SLS and ULS analysis using the same model is efficient and beneficial for all parties involved in the design process. This has stimulated the development of finite element based methods to define safety in a geotechnical context, such as the method of phi-c reduction or strength reduction (Brinkgreve & Bakker, 1991; Griffith & Lane, 1999) to calculate a *global* factor of safety. This method has proven its usefulness over the last decades. The introduction of Eurocode 7 has inferred the need to incorporate different combinations of *partial* safety factors for Actions (loads), Materials and Resistances, according to the various design approaches as defined in Eurocode 7. In the FEM, external loads and materials are considered input data. The use of partial factors for loads and material properties can simply be dealt with at input level. Actions and resistances from the soil, on the other hand, are not known a priori. They depend on the local stress conditions and may change during the analysis. This makes it difficult to apply partial factors on actions and resistances coming from the soil. Alternatively, Eurocode 7 allows for partial factors on 'Action effects', which can be interpreted as the resulting structural forces (forces in anchors and struts, bending moments in walls, etc.). In this way, it is feasible to use partial factors according to the different design approaches using the FEM.

The time that geotechnical engineers only work in local areas with one design code is far behind us. The work has become international. The introduction of Eurocode 7 is a first step towards harmonization. However, different countries have selected different design approaches and defined different sets of partial factors in their national annexes. This makes the use of partial factors in daily design calculations error prone, in particular when using the FEM. To overcome this, the finite element software may provide facilities to efficiently manage the different design approaches with coherent sets of partial factors, to assign the factors to the various components of the finite element model, to distinguish between SLS and ULS calculations, and to assist users in selecting the required design approach for the ULS calculations in their project. In the following paragraph it is described how this process can be facilitated.

2.1 Workflow and calculation schemes for ULS calculations

The typical work flow in a 'standard' finite element analysis is the following:

1. Create geometry and boundary conditions
2. Specify and assign material properties
3. Generate finite element mesh
4. Generate initial conditions
5. Define calculation phases
6. Perform calculations
7. Inspect results

In this respect, the work flow for ULS calculations is not different than for SLS calculations. However, one need to decide on how and when to change the loads and properties when going from SLS calculations to ULS calculations for the same model. Here, it is suggested to first complete the 'normal' work flow with characteristic values of input parameters (SLS) before considering ULS conditions.

After a successful SLS calculation, partial factors may be defined (if not yet available) and applied to the corresponding loads and materials in the model. Partial factors for action effects (structural forces) only need to be applied after the calculation. Partial factors that are not explicitly defined are equal to unity, such that characteristic values are used for the corresponding properties. Coherent sets of partial factors according to a particular design code (country-dependent) (herein named a 'Design Approach'; see Figure 1) may be assembled and stored under a unique and recognizable name in a global data base. Once a Design Approach has been defined and stored, it can be re-used in other projects that are governed by the same design code.

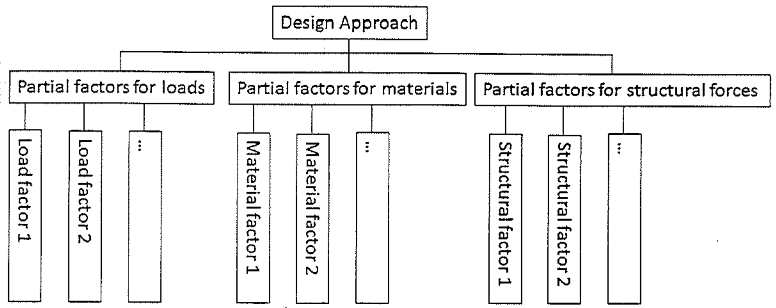


Figure 1: Schematic overview of a Design Approach (coherent set of partial factors)

Regarding partial factors for loads, distinction should be made between different 'load factors'. Eurocode 7 differentiates between *Permanent* and *Variable* actions; both can be *Unfavourable* or *Favourable*. Within a Design Approach, different load factors may be defined with a unique and recognizable description (a 'label'; for example *Permanent unfavourable*). In the finite element model, 'load labels' should be assigned to all external loads, referring to the applicable load factor, such that they [automatically] obtain the right partial factor from the applicable Design Approach when ULS calculations are performed. It should be realised that the effect of a load (favourable or unfavourable) may differ from one calculation phase to another. Therefore, load labels that are assigned to external loads during the creation of the finite element model may need to be changed as part of the definition of a calculation phase.

Regarding partial factors for materials, it is assumed that material properties for individual soil layers are stored as model parameters in material data sets. The use of partial factors on materials may lead to the [automatic] creation of 'shadow' material data sets that are [automatically] used in ULS calculations instead of the original ones, assuming that the original data sets have been created using characteristic values of model parameters. In the framework of the Design Approach concept, partial factors for model parameters ('material factors') are defined with a unique and recognizable description. In the material data sets, 'material labels' should be assigned to all model parameters, referring to the corresponding material factor.

Let's consider the use of the simple linear-elastic perfectly-plastic model with Mohr-Coulomb failure contour to describe the behaviour of a soil layer. In principle, different material labels can be defined for each of the parameters. We can identify general properties (γ), elasticity properties (E, ν) and strength properties (c, φ, ψ). Different material labels can be defined for the cohesion c and the friction angle φ. However, the strength parameters can be used as effective strength properties (c', φ', ψ) in an effective stress approach, or as undrained strength properties ($c = s_u$; $\varphi = \psi = 0°$) in an undrained total stress approach. The latter case is actually known as the Tresca model, but this can be regarded as a special case of Mohr-Coulomb. According to Eurocode 7, different partial factors are defined for c' and s_u. Hence, a further distinction should be made in material factors and labels when defining partial factors for the Mohr-Coulomb model parameters, depending on whether the c-parameter is used as an effective cohesion c' or as an undrained shear strength s_u.

In a similar way, a material factor can be defined for unit weight (γ) for materials that are primarily used as external loads. Note that material factors are typically used to *decrease* parameter values whereas load factors are typically used to *increase* values, so in this case the material factor should correspond to the *inverse* of the applicable factor for external load.

It should be noted that some advanced models have parameter-dependencies and there are limitations in the values or ratios that those parameters can have. Therefore, it has to be checked that applying material factors does not lead to impossible ULS parameter values or ratios.

Regarding partial factors for structural forces, in principle only one 'structural factor' is needed which is applied to all structural forces. However, the Design Approach concept allows for different structural factors to be defined with a unique and recognizable name ('structural label'). In that case, each (type of) structure or structural force in the finite element model should be assigned a structural label, referring to the corresponding partial factor for structural forces.

In order to perform design calculations, new calculation phases need to be defined in addition to the SLS phases. To indicate whether a calculation phase is a design calculation (ULS), the applicable Design Approach needs to be selected for that phase. In such phases the corresponding load factors are [automatically] applied to the loads and the material factors are [automatically] applied to the model parameters (using the 'shadow' material data sets) based on their labels, whereas phases for which no Design Approach has been selected use the original (characteristic) values. Once the different Design Approaches as well as the 'labels' have been properly defined, changing from one design approach to another is easy and virtually free of error.

There are two possible schemes to perform ULS calculations in relation to SLS calculations (Bauduin et al., 2000).

Scheme 1:

0. Initial state		
1. Phase 1 (SLS)	➢	4. Phase 4 (ULS)
2. Phase 2 (SLS)	➢	5. Phase 5 (ULS)
3. Phase 3 (SLS)	➢	6. Phase 6 (ULS)

In the first scheme the design calculations (ULS) are performed for each serviceability state calculation separately. This means that Phase 4 starts from the resulting stress state of Phase 1, Phase 5 starts from Phase 2, etc. Note that in this case a partial factor on a material stiffness parameter is only used to calculate *additional* displacements as a result of stress redistributions due to the factored (higher) loads and the factored (reduced) strength parameters. It is anyhow questionable what the meaning is of displacements obtained from ULS calculations.

Scheme 2:

0. Initial state ➢ 4. Phase 4 (ULS) ➢ 5. Phase 5 (ULS) ➢ 6. Phase 6 (ULS)
1. Phase 1 (SLS)
2. Phase 2 (SLS)
3. Phase 3 (SLS)

In this scheme, the design calculations (ULS) start from the initial situation and are performed subsequently. This means that Phase 4 starts from the Initial state, Phase 5 starts from the resulting stress state of Phase 4, etc. In general, it is recommended to establish the initial stress field from characteristic values of K_0 (however, some exceptions may occur); see also Frank et al. (2004).

Design calculations that finish successfully (without failure) can be regarded as 'fulfilling the requirements of the design code'; at least with respect to the partial factors in ULS design. However, a careful check on the results remains necessary.

In the post-processing after the design calculations, the structural factors are [automatically] applied to the calculated values of structural forces in order to obtain their design values. Note that SLS requirements should be checked on the basis of the corresponding SLS calculation results rather than from the ULS results.

In this section it has been indicated [in square brackets] where the Design Approaches concept can be automated in finite element software. If that is done, it is essential for the user to be able to view which values of loads, material properties and structural forces are actually used in the ULS calculation. Transparency is necessary such that the user (geotechnical engineer) can check those values and maintains his / her responsibility for the geotechnical design.

3 Case: ULS design of an embedded sheet pile wall

This example presents the calculation of the Structural and Ground Limit State of an embedded sheet-pile wall. The case is based on example 9.2 from the Eurocode 7 document (European Committee for Standardization, 2004). The geometry of the situation is shown in Figure 2. The wall has a nominal excavation depth of 5 m. and an additional excavation depth of 0.4 m (due to accidental over-dig) is foreseen. The wall is supported by one row of anchors at an elevation level of -1.0 m (anchorage inclination is 10 degrees downward). The free anchor length is 11 m and the length of the anchor body is approximately 6.5 m.

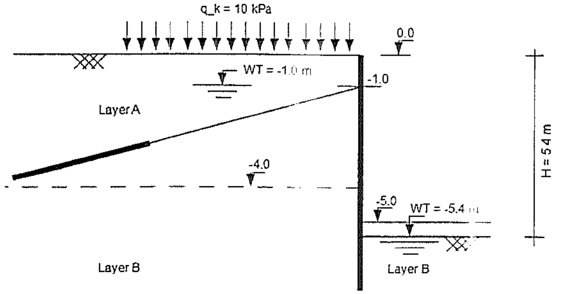


Figure 2: Geometry of the embedded sheet pile wall

The ground profile consists of two layers. A relatively soft soil layer is overlain by a 4 m thick stiffer layer. The characteristic properties of these layers in terms of model parameters for the Hardening Soil model are presented in Table 1. The initial phreatic level is 1.0 m below ground surface. In this example the long term situation is analysed so only drained behaviour is considered and effective stress parameters are presented. For the different layers we use the following water conditions:

- Layer A & B: Hydrostatic, according to initial phreatic level at ground surface -1 m
- In the phases with dewatering: Steady-state situation (calculated by steady-state groundwater flow based on the head difference as a result of the lowered water table inside the excavation), assuming the lowered water table is equal to the excavation level in each phase, the sheet pile wall is impermeable and the bottom of the model is closed for flow.

Table 1: Characteristic soil properties

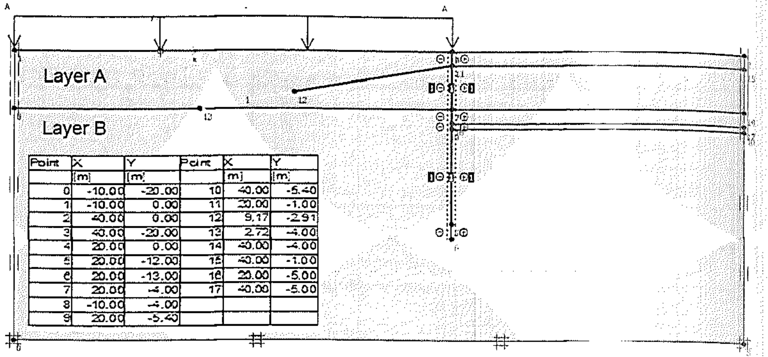
Parameter	Layer A	Layer B	Unit
Material model	Hardening Soil	Hardening Soil	
Behaviour	Drained	Drained	
Unit weight $\gamma_{unsat} / \gamma_{sat}$	18 / 20	20 / 20	kN/m^3
E_{50}^{ref} *)	20000	12000	kN/m^2
E_{oed}^{ref} *)	20000	8000	kN/m^2
E_{ur}^{ref} *)	60000	36000	kN/m^2
Power m	0.5	0.8	-
Poisson's ratio ν	0.2	0.2	-
Cohesion c'	1.0	5.0	kN/m^2
Friction angle φ	35	24	°
Dilatancy angle ψ	0	0	°
Normally-consolidated stress ratio K_0^{nc}	0.50	0.59	-
Failure ratio R_f	0.9	0.9	-
Tensile strength σ_t	0.0	0.0	kN/m^2
Interface strength ratio	0.67	0.67	-
Initial stress ratio K_0	0.50	0.95	-
Permeability	1.0	0.001	m/day

*) Reference stiffness at a reference stress level of 100 kN/m^2

Other parameters used in the calculation are:

- Variable surcharge load of 10 kN/m^2 on the active side of the wall
- Embedment depth of the sheet-pile wall pre-determined at -12 m (wall length 12 m)
- Steel sheet-pile wall: EA=3.675·10^6 kN/m, EI = 5·10^4 kNm^2/m, no corrosion considered, weight 1.4 kN/m/m
- Anchor stiffness: EA = 16.5·10^3 kN/m
- Anchor pre-stress force, applied only when the anchor is installed: 100 kN/m

The geometry used to create the finite element model is presented in Figure 3.



Point	X [m]	Y [m]	Point	X [m]	Y [m]
0	-10.00	-20.00	10	40.00	-5.40
1	-10.00	0.00	11	20.00	-1.00
2	40.00	0.00	12	9.17	-2.91
3	40.00	-20.00	13	2.72	-4.00
4	20.00	0.00	14	40.00	-4.00
5	20.00	-12.00	15	40.00	-1.00
6	20.00	-13.00	16	20.00	-5.00
7	20.00	-4.00	17	40.00	-5.00
8	-10.00	-4.00			
9	20.00	-5.40			

Figure 3: Geometry used to create the finite element model

The safety philosophy is introduced using the following starting points and assumptions:

- For this example it is chosen to use both EC7-DA2 as well as EC7-DA3 for the structural (STR) and ground (GEO) Limit State verification. The partial factors are taken from EC7, appendix A, as presented in Table 2 and 3.
- No partial factors are applied to the properties of structural elements.
- It is assumed that all water levels are strictly controlled, so no additional safety surcharge is applied on water conditions during ULS.
- Accidental over-dig is taken into account, so an additional excavation depth is applied in the ULS calculations.
- In this example no stiffness variation for soil and structural elements is applied during the ULS calculations.
- In this example only an unfavourable load factor is used for the (variable) surcharge load; in practice it might also be necessary to investigate the effect of favourable load factors.

Table 2: Partial factors on actions (STR/GEO LS, default values according to EC7, annex A)

Action		EC7-DA2	EC7-DA3
Permanent	Unfavourable	1.35	1.00
	Favourable	1.00	1.00
Variable	Unfavourable	1.50	1.30
	Favourable	0.00	0.00

Table 3: Factors on soil parameters (STR/GEO LS, default values according to EC7, annex A)

Soil parameter	EC7-DA2	EC7-DA3
Angle of shearing resistance (tan φ)	1.00	1.25
Effective cohesion	1.00	1.25
Undrained shear strength	1.00	1.40
Weight density	1.00	1.00

The aforementioned Design Approach facility, as implemented in PLAXIS 2D, has been used to elaborate this case; both according to EC7-DA3 and EC7-DA2. In the latter case, partial factors are used on the *action effects* by multiplying the resulting structural forces (obtained with characteristic values for the soil properties) with an appropriate partial factor for the action effects. This approach is often indicated as EC7-DA2*. The following practical method is used: At input, a factor of 1 is used for the permanent unfavourable loads (instead of 1.35) and a factor of 1.5 / 1.35 = 1.11 is used for the variable unfavourable loads (instead of 1.5). From the output, the action effects (i.e. the structural forces) are then multiplied by a factor of 1.35.

Table 4: Calculation phases

	Phase	State	Phase no.	Start from phase	Calculation type
	Initial	SLS	0		K_0-procedure
	Activate wall	SLS	1	0	Elasto-plastic
	Surcharge 10 kPa + excavate to -1m	SLS	2	1	Elasto-plastic
	Active anchor + pre-stressing 100 kN/m	SLS	3	2	Elasto-plastic
	Full excavation + dewatering to -5.0m	SLS	4	3	Elasto-plastic
	Full excavation + dewatering to -5.4m (including over-dig)	SLS	5	4	Elasto-plastic
Scheme 1	**ULS long term Phase 2**	ULS	6	2	Elasto-plastic
	ULS long term Phase 3	ULS	7	3	Elasto-plastic
	ULS long term Phase 4	ULS	8	4	Elasto-plastic
	ULS long term Phase 5	ULS	9	5	Elasto-plastic
Scheme 2	**Surcharge 10 kPa + excavate to -1m**	ULS	10	1	Elasto-plastic
	Active anchor + pre-stressing 100 kN/m	ULS	11	10	Elasto-plastic
	Full excavation + dewatering to -5.0m	ULS	12	11	Elasto-plastic
	Full excavation + dewatering to -5.4m (including over-dig)	ULS	13	12	Elasto-plastic

In the example the drained stress history is used to analyse the SLS and ULS of the structure. For demonstration purposes, both Scheme 1 and Scheme 2 have been applied to perform design calculations in relation to the serviceability calculations. In general. it is sufficient to choose only one scheme. The modelled calculation phases are listed in Table 4. The results of the calculations in terms of the design values of structural forces are presented in Table 5.

Table 5: Calculation results

Phase	Max. hor. wall def. [mm]	Max. anchor force [kN/m]	Max. bending moment [kNm/m]	Max. anchor force [kN/m] EC7-DA2*	Max. bending moment [kNm/m] EC7-DA2*
Initial	-				
Activate wall	-	-	-		
Surcharge 10 kPa + excavate to -1m	1	-	-4		
Active anchor + pre-stressing 100 kN/m	-10	100	34		
Full excavation + dewatering to -5.0m	50	119	173		
Full excavation + dewatering to -5.4m (including over-dig)	70	130	215		
		EC7-DA3		EC7-DA2*	
ULS long term Phase 2		-	-6	-	1.35*-4 = -5
ULS long term Phase 3		100	36	1.35*100 = 135	1.35*34 = 46
ULS long term Phase 4		138	236	1.35*120 = 162	1.35*177 = 239
ULS long term Phase 5		164	326	1.35*130 = 176	1.35*220 = 297
Surcharge 10 kPa + excavate to -1m		-	-7	-	1.35*-4 = -5
Active anchor + pre-stressing 100 kN/m		100	28	1.35*100 = 135	1.35*33 = 45
Full excavation + dewatering to -5.0m		147	261	1.35*120 = 162	1.35*175 = 236
Full excavation + dewatering to -5.4m (including over-dig)		168	340	1.35*131 = 177	1.35*218 = 294

Considering the results, some general observations can be made:

- Using scheme 1 or scheme 2 gives fairly similar values in structural forces for both EC7-DA2* and EC7-DA3 (in this example). It should be realised that differences may be larger in other situations.
- For a number of phases EC7-DA2* gives relatively large values for the anchor force compared to EC7-DA3, which is the result of the fact that the pre-stress value is entered as a characteristic value in EC7-DA3.

Note that in Schweiger (2010) a slightly different approach is presented for EC7-DA2*, where calculations are performed without (case 1) and with (case 2) the variable unfavourable load. The design values of structural forces are then obtained by the sum of the results for case 1 with the partial factor for permanent unfavourable load, and the difference in results between case 2 and case 1 with the partial factor for variable unfavourable load, i.e.

$$F_{design} = F_{case1} * 1.35 + (F_{case2} - F_{case1}) * 1.50 \quad (1)$$

The latter approach would be more difficult to automate than the approach described in this contribution. It should be noted that both approaches are approximations of the original EC7-DA2.

4 Conclusions

In this contribution a concept is presented to facilitate ultimate limit state calculations in a finite element environment, in addition to regular serviceability state finite element calculations. The focus has been on a number of issues relevant for defining and assigning sets of partial safety factors and explaining the work flow required for working with design approaches. An example has been elaborated in which both EC7-DA2 and EC7-DA3 have been used in order to show the possibilities for working with Eurocode 7. EC7-DA1 has not been considered, but this can be regarded as a combination of the other two design approaches.

The purpose of this contribution is to demonstrate how the Design Approaches facility can be used as an efficient facility in finite element software to perform geotechnical ultimate limit state design calculations. It is NOT the authors' intention to advocate a particular design approach.

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Bodenverbesserungssäulen als Präventation der Bodenverflüssigung bei Erdbebenbeanspruchung

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Kurzfassung: Die Anwendung von Schotter- oder Betonsäulen zur Verhinderung von Bodenverflüssigung hat in den letzten Jahren zugenommen. Untersuchungen zu deren Funktionsweise sind jedoch kaum vorhanden. Dies lässt sich damit begründen, dass sowohl numerische Berechnung mit einfachen Stoffmodellen als auch kleinmaßstäbliche Laborversuche problematisch sind. In diesem Beitrag wird die Anwendung von Bodenverbesserungssäulen als Prävention zur Bodenverflüssigung numerisch untersucht. Hierfür wurde ein hypoplastisches Modell verwendet. Das Augenmerk der Untersuchung liegt dabei auf dem Einfluss von Steifigkeit und Durchlässigkeit der Säulen. Weiterhin wird der Unterschied zwischen Schotter- und Betonsäulen sowohl in 2D- als auch in 3D-Modellen betrachtet.

Abstract: the application of gravel or concrete columns to prevent the soil liquefaction has increased in the last few years. However, for understanding of this method, detailed investigations are still lacking. Numerical analyses with simple constitutive models and small scale experiments are not suitable. In this paper, a numerical with a hypoplastic constitutive model is presented. The influence of stiffness and permeability of the columns are examined separately. Furthermore, the difference between gravel and concrete columns is studied in 2D and 3D models.

1 Einführung

Durch Erdbeben entstehen enorme wirtschaftliche Schäden. Diese Schäden sind oft mit einer Bodenverflüssigung verbunden. Als innovative Methode zur Verminderung der Verflüssigungsgefahr kamen in den letzten Jahren die Bodenverbesserungssäulen zum Einsatz. Als Bodenverbesserungssäulen werden in der Regel Schotter- oder Betonsäulen bezeichnet. Während die Betonsäulen allein durch ihre hohe Steifigkeit die Verflüssigung verhindern können, wirken die Schottersäulen gegen Verflüssigung mit verschiedenen Mechanismen entgegen (Dränage, Verdichtung und Stützung (Madhav et al. 2008)).

Aufgrund der hohen Durchlässigkeit der Schottersäulen im Vergleich zum umliegenden Boden baut sich in den Säulen kaum ein Porenwasserdruck (PWD) auf. Der Druckunterschied verursacht eine Wasserbewegung in Richtung der Säulen und damit eine Abnahme des PWDs im Boden. Da die Durchlässigkeit beim Sand und Schotter in der horizontalen Richtung größer als in der vertikalen Richtung ist, ist der Einfluss der Schottersäulen nicht nur die Abkürzung der Dränagewege, sondern auch die Änderung der Wasserbewegung zu der effektiveren Dränagerichtung zu wechseln (Madhav et al. 2008). Zusätzlich bewirkt der Einbau der Schot-