Summary and conclusions

The thesis traces the research into the constitutive modelling of fine-grained soils using theory of hypoplasticity. The developed constitutive model is from the practical point of view equivalent to the Modified Cam clay model, since it requires the same number of material parameters with an equivalent physical meaning. However, due to the non-linear character of the hypoplastic formulation, the quality of predictions by the proposed model is at least comparable to more complex advanced elasto-plastic models.

From the mathematical standpoint, the model is positively homogeneous of degree 1 in D and for a given value of f_d in T. Therefore, the behaviour of the fine-grained soil is assumed to be rate-independent. This is clearly a strong assumption that limits the validity of the material parameters only to certain range of loading rates. Positive homogeneity of degree 1 in T for given f_d implies parallel normal compression lines of the slope λ^* in the $\ln(1 + e)$ vs. $\ln p$ space. Also, the behaviour is for a given degree of overconsolidation assumed to be scalable by the mean stress, which is according to experimental evidence a reasonable approximation of the behaviour of clays.

The model requires four other material parameters in addition to λ^*. N determines the position of the isotropic normal compression line, κ^* the slope of the isotropic unloading line in the $\ln(1 + e)$ vs. $\ln p$ space. Unlike in the Cam clay-type models, the slope of the unloading branch is exactly equal to the parameter κ^* only for unloading from the isotropic normally consolidated state, at overconsolidated states the slope is higher, due to the non-linear character of the model formulation. The next parameter, ϕ_c, defines the critical state friction angle at triaxial compression and extension. The model makes use of the Matsuoka-Nakai shape of the critical state locus in the stress space, so for other Lode angles the critical state friction angle is slightly higher than ϕ_c. This is well in agreement with experimental data. The last parameter, r, controls the shear stiffness, which decreases with increasing r. This parameter is usually calibrated by means of a parametric study.

A shortcoming of hypoplastic models in general is an inevitable ”rachetting”, i.e. the extensive accumulation of strains during cyclic loading caused by the too soft response upon sharp reversals of the stress/strain paths directions. Niemunis and Herle [108] proposed a modification of the hypoplastic equation by introducing so-called intergranular strain concept that eliminates this shortcoming. The proposed model has been designed to be used with the intergranular strain enhancement by letting the tensor L to have the form appropriate to predict both the behaviour in the small strain range and upon sharp path reversal (in this case the nonlinear part $N\|D\|$ of the hypoplastic equation is ruled out) and for continuing deformation (in limit the model response tends to the basic hypoplastic formulation).

It has been shown that the proposed form of the constitutive tensors L and N and the barotropy and pyknotropy factors f_d and f_s allow us to derive a closed-form solution for swept-out-memory states, which compose a hypersurface in the stress – void ratio space called swept-out-memory surface[1]. This surface is a close approximation of the state boundary surface, defined as boundary of all possible states in the stress – void ratio space. Prediction of the state boundary surface is an important property of the proposed model that makes it possible not only to compare the model response with relevant experimental data, but mainly it opens the way for further extensions of the model. The study in Chapter 3 revealed an important shortcoming of the model – the swept-out-memory surface does not have a reasonable shape for too high values of the ratio κ^*/λ^*. However, if κ^*/λ^* is smaller than approx. 1/4, the shape of the state boundary surface compares well with the shape observed experimentally.

Predictions by the proposed model were compared with a number of existing elasto-plastic and hypoplastic models, namely Modified Cam clay model, three surface kinematic hardening (3-SKH) model and a Grenoble-type hypoplastic model (CLoE). With regard to the directional response, the proposed model, together with the 3-SKH model, performed best.

As expected, a simple Modified Cam clay model has shown a poor performance for loading paths directed inside the elastic region, while the non-linear character of the hypoplastic model led to at least qualitatively correct predictions for all loading directions. Predictions of stress probes that followed after sharp stress-path reversal were further improved by applying the intergranular strain concept. The 3-SKH model performed similarly to the proposed hypoplastic model. This is a consequence of the fact that although both models are developed using different mathematical concepts, they are both based on the similar physical interpretation of the behaviour of fine-grained soils.
A study of the validity of a single set of material parameters for prediction of behaviour of soils at different overconsolidation ratios (OCR) revealed that if the proposed hypoplastic model is calibrated at higher OCR, it performs well for a broad range of OCRs, both qualitatively and quantitatively. The Modified Cam clay model and the 3-SKH model performed in this case worst than the proposed hypoplastic model.
The last part of the thesis demonstrated a possibility for further extension of the model. In particular, the basic model was modified to predict the behaviour of clays with meta-stable structure. The framework for the mechanical behaviour of natural clays by Cotecchia and Chandler [34], according to which it is possible to relate the behaviour of natural and

[1]This closed-form solution is not available for other hypoplastic models, such as the model by von Wolffersdorff [141]

reconstituted clay through the state variable sensitivity, was applied. The sensitivity was incorporated in such a way that the size of the state boundary surface was increased, other material properties were however kept unchanged. A suitable evolution equation for sensitivity then enabled us to predict the behaviour of clays with meta-stable structure. Predictions of the enhanced hypoplastic model were compared with predictions by its elasto-plastic 'equivalent', structured Modified Cam clay model, developed in Chapter 7. It was again clearly demonstrated that with the same number of parameters of equivalent physical interpretation the non-linear hypoplastic model leads to better predictions.