

Simulation of long-term consolidation behavior of soft sensitive clay using an elasto-viscoplastic constitutive model

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Given the recent tendency to port connectivity and other infrastructure development projects, the need for the construction of embankments on soft sensitive soils is increasing. Soft sensitive soils are fine-grained sediments with moderate to high clay fraction that are usually deposited in a marine environment. Soft sensitive clays are usually characterized by high compressibility and low shear strength. Construction and maintenance of embankments on soft sensitive clay are challenging and create numerous complexities for designers and geotechnical engineers. Although much attention has been paid for understanding the behavior of embankments on soft sensitive soils in the last few decades, optimal design of such embankments still remains difficult, and their long-term performance is largely dependent on the design factor of safety. This is mainly because of the unavailability of a proper analysis tool for the accurate prediction of long-term consolidation response of soft sensitive clay foundation beneath the embankment. Rational prediction for long-term consolidation response of soft sensitive clay deposits has been an active research since long. Depending on soil conditions, excess pore water pressures sometimes increase or become stagnant over a period of time following the end of loading. During the period of pore water pressure stagnation or increase, ground deformations, especially the lateral displacements, also increase with time. This type of anomalous soil behavior after completion of embankment construction has been pointed out in the literature. Crooks *et al.* [1] reported anomalous pore water pressure generation in 11 of 31 case studies. The anomalous pore water pressure generation as well as continuous large displacements has also been observed for the test embankments over the soft sensitive Champlain clay at Saint Alban [2–4]. Similar behaviors have also been reported by many researchers [2, 5, 6]. The phenomenon is thus quite common.

There are various possible explanations for the anomalous pore water pressure generation and continuing large deformation after the end of construction of embankments. Mesri and Choi [7, 8] have pointed out that the additional pore water pressures during consolidation are generated because of the collapse of clay structure. In the 20th Terzaghi lecture, Mitchel [9] described the anomalous pore water pressure generation during consolidation as a result of the structural degradation of soft sensitive overconsolidated clay when the current stress state exceeds the preconsolidation pressure. He further pointed out that this anomalous behavior leads to a significant increase in compressibility accompanied by considerable decrease in permeability that greatly slow down the rate of consolidation. Olson [10] pointed out that if the creep rate is high relative to soil permeability, creep-induced pore water pressures are developed and may delay large ground deformations. Tavenas and Leroueil [11], Leroueil *et al.* [12], and Leroueil and Marques [13] report that pore water pressure can increase even after the

end of construction of the embankment when the strain-rate-dependent limit state surface is subjected to contraction and the effective stress state is bounded by it.

Anomalous phenomenon of pore water pressure increase and associated other soil responses have not been successfully simulated till now. Yin and Zhu [14] have qualitatively generated the increase of excess pore water pressure after the construction of the embankment at Tarsiut Island in the Canadian Beaufort Sea, considering the creep nature of the clay that cause volumetric compression. Oka, Tavenas, and Leroueil [15] introduced strain-softening effect into the elasto-viscoplastic constitutive model developed by Adachi and Oka [16] in order to describe the structural breakdown of clay due to the passing of stress path through the limit state surface. They concluded that the destructuration of soil structure has significant effect on pore water pressures as well as on displacements, especially during long-term prediction. However, it has not been possible to successfully reproduce the field anomalous soil behavior during consolidation. Studying the behavior of the Berthierville test embankment with an elasto-viscoplastic model, Kim and Leroueil [17] concluded that it is necessary to add structure collapse to the viscous effect to explain pore pressure observations.

The primary objective of the present paper is to configure an elasto-viscoplastic constitutive model [18] for two-dimensional long-term consolidation analysis of soft sensitive clay, so that it could successfully reproduce the unusual field behavior including the anomalous pore water pressure generation and continuing large deformation after the end of construction. The constitutive model is an extension of the original elasto-viscoplastic model for water-filled geomaterials proposed by Adachi and Oka [16] with an inclusion to account for the soil-structure degradation and anisotropy of clay [19]. The adopted constitutive model can reasonably describe some of the important features of natural soft clay including strain rate sensitivity, structural degradation or strain softening, strain hardening, creep, secondary compression, and stress relaxation. For numerical simulation and validation, soil parameters and field observations are related to the test embankments built over the soft sensitive Champlain sea clay at Saint Alban, west of Québec city, Canada, that exhibited anomalous pore water pressure generation and continuing large ground deformation even after the end of construction of the embankment [2, 4, 20, 21]. As for the numerical tool, the FEM is used under the framework of updated Lagrangian finite deformation theory (FDT). An automatic time increment selection scheme is implemented on the basis of earlier work made by Karim and Oka [22]. It has proven to be effective where strain rate sensitivity plays an important role and efficient in long-term computation. This time increment selection approach is investigated further in this paper for the updated Lagrangian finite element framework.

The paper is organized as follows. In Section 2, there is a brief description of the elasto-viscoplastic constitutive model considering structural degradation. Section 3 describes the updated Lagrangian finite element framework based on the FDT. In Section 4, the employed automatic time increment selection scheme for the long-term consolidation response of geomaterials is briefly presented. In Section 5, construction loading of the test embankments as well as soil conditions and viscoplastic

model parameters for Champlain clay at Saint Alban are presented. Performance of this FEM model is thoroughly investigated in Section 6, by comparing the predicted results with the field soil responses beneath the test embankments at Saint Alban.

ELASTO-VISCOPLASTIC CONSTITUTIVE MODEL FOR CLAY

Brief description of the elasto-viscoplastic constitutive model considering soil structural degradation [18,19] is presented in this section. This model is an extension of the rate-dependent elasto-viscoplastic constitutive model for water-filled clay proposed by Adachi and Oka [16] to consider the soil structural degradation. Therefore, like the original model [16], this model combines the Cam-clay model [23] and Perzyna's [24] overstress type of viscoplasticity for the elasto-viscoplastic formulations. In this model, the structural degradation is described by means of the shrinkage of both overconsolidation (OC) boundary surface and the static yield surface through the softening of viscoplastic strain.

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