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Research Paper

A Modified Mohr-Coulomb Model to Simulate the Behavior of Pipelines in Unsaturated Soils

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ABSTRACT

At the present time, it is very common in practice to utilize Mohr-Coulomb model to simulate the soil behaviour in the application of soil-pipeline interaction problems. However, the traditional Mohr-Coulomb model is unable to predict the realistic loading that can apply on buried pipes during large ground deformation. Especially, the linear elastic-perfectly plastic Mohr-Coulomb model is not capable of simulating the unsaturated soil loading which can result larger than anticipated loading due to suction induced additional normal force between the soil particles. A user defined unsaturated modified Mohr-Coulomb model is developed within a generalized effective stress framework considering suction hardening effects to capture the realistic loading induced by unsaturated soil medium. Firstly, the model has been developed considering microscopic and macroscopic suction hardening mechanisms, and was implemented into a commercial finite element program associated with user subroutine written in FORTAN. Then the model was validated through a series of unsaturated triaxial compression tests conducted on the basis of different sand types having various initial conditions. Finally, the model has been applied to simulate the behaviour of pipelines subjected to lateral soil loading in unsaturated soils. The results revealed that the modified Mohr-Coulomb model has reasonable predictions when compared to the load-displacement response of pipes obtained from two large scale testing programs. The developed model can be used to predict the increased strength and stiffness associated with soil suction that increases lateral loads on pipelines, and thus has widespread relevance for simulating the pipeline response in unsaturated soils under externally imposed ground movement.

1. Introduction

Pipelines used for the transport of energy and services are important lifelines in the modern society. The vital role that they play in the present economy is reflected by many kilometers of pipelines laid across large geographical areas. They are often buried underground for protection and support, but large ground deformations can induce catastrophic failures on the pipeline. Progressive ground deformations such as caused by landslides or earthquakes can induce pipeline deformation impacting serviceability or trigger failures such as buckling or wrinkling. The earthquakes occurred in Turkey (Kocaeli), Taiwan (Chi-Chi) and Japan (Sanriku and Niigataken Chuetsu-oki Earthquake) offer numerous examples of the damage to the pipelines (Fig. 1). The damage caused by ground deformation can be further enhanced by the presence of suction in the unsaturated medium where the pipes are usually constructed.

The investigations on the behaviour of pipes subjected to external loading have been extensively studied for the last 10 decades [21,40,19,10,4,40,16]. However, little attention is devoted until recently on the investigations of moisture influence of buried pipes subjected to large ground deformation. The recent large scale experiments conducted at Cornell University, US [26,24,25,15,27] and Tokyo Gas Co Ltd, Japan [29] on pipes buried in unsaturated soil were able to highlight the significance of considering soil saturation when assessing the pipe responses under large ground deformation. For example, the results from the large scale tests revealed that the response of buried pipes under external loading can significantly be influenced by the partial saturation of soil depending on the soil type, leading modifications to current design standards that were developed on the basis of pipes tested in dry/fully saturated tests. These studies will assist for better understanding of the behaviour of soil-pipeline system, thus to provide backbone in the response predictions of buried pipes using numerical modelling approaches.

The development of numerical analysis and its application to geotechnical engineering problems over the past 20 years have

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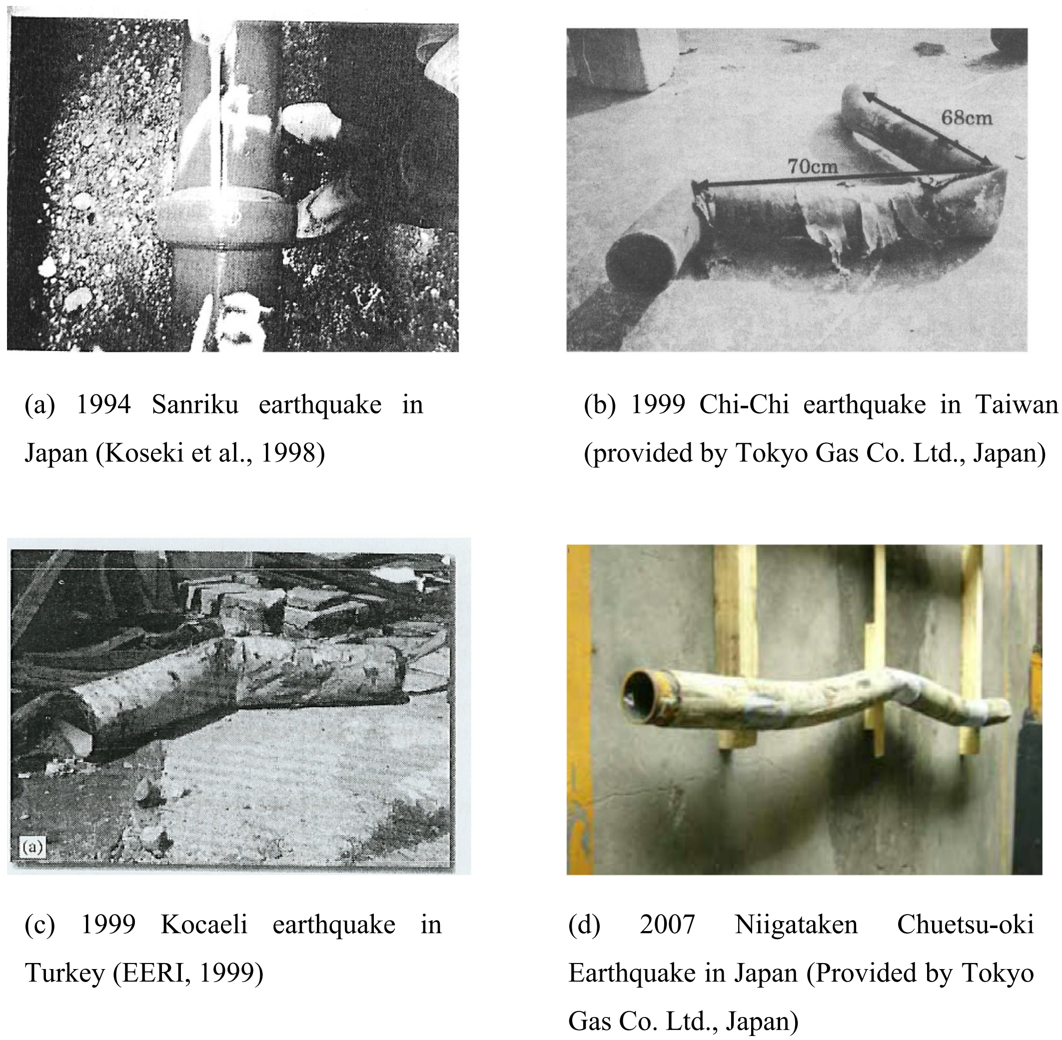

Fig. 1. Failures of steel pipelines due to earthquakes. (See above-mentioned references for further information.)

provided geotechnical engineers with an extremely powerful analysis tool [28]. They facilitate to assess the response of pipes considering wide range of variables in timely and efficient manner. The most recent research work conducted in the area of numerical modelling of soil-pipeline interaction problems has been able to highlight the development of proper numerical tools to capture the realistic behaviour of pipelines when subjected to ground movements. For example, Yimsiri et al. [46] have adopted state dependent hardening/softening model (Nor-Sand [12]) to study the behaviour of pipelines subjected to lateral ground deformation. Cheong et al. [9] also used the Nor-Sand model to investigate the response of elbow pipelines subjected to lateral ground deformation. Chatterjee [7] has adopted modified Cam-Clay model [36] to quantify the lateral resistance of pipes in soft soil. Bryden et al. [6] have used hyperbolic hardening soil model, which can capture the stress-dependent variation in stiffness to study the effect of surface loading on buried pipelines. The uses of such advanced soil constitutive models were effective for predicting the behaviour of pipelines due to their superior capability of capturing the load dependent material state changes. However, in most occasions, they demand comprehensive calibration of soil parameters using detailed and advanced testing programs prior to use in the desired application. On the other hand, it is very common in practice to utilize standard material models such as Mohr-Coulomb model to simulate the soil behaviour in the application of soil-structure interaction problems [8,44,1,37,15]. These models are often chosen considering its simplicity, ease of use, reasonable computational time and the high level of understanding among the engineers. Such models are readily available in commercial finite element programs so that researchers/practitioners can use them at less cost. However, they have their own limitations which can significantly influence the prediction of buried pipeline response unless appropriate model changes are incorporated.

The linear elastic-perfectly plastic Mohr-Coulomb model is unable to predict the realistic loading that can apply on buried structures during large ground deformation. Especially, the original Mohr-Coulomb model is not applicable to simulate the unsaturated soil loading which can result larger than anticipated loading due to suction induced additional normal force between soil particles. Recent studies showed that soil suction under unsaturated condition can change the stiffness and strength, affecting the behaviour of the pipeline systems subjected to ground deformation [25,15,38,33,35,31]. Therefore, utilization of traditional Mohr-Coulomb failure criterion could lead to under-estimation of soil loads on pipes, thus could result in unexpected pipeline failures in the events of construction or earthquake induced ground deformations. This study showed that Mohr-Coulomb model could well be used to predict realistic pipeline loading if it can be modified to include the suction into the constitutive modelling framework. A user defined unsaturated modified Mohr-Coulomb model is