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ELASTOPLASTICITY OF GRAVEL PROTECTING ROCKFALL-ENDANGERED STEEL PIPELINES

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Summary This contribution deals with the development of a numerical model providing reliable estimates of the loading of a gravel-buried steel pipe subjected to rockfall. The reliability test is based on two physically and statistically independent sets of experiments. The first set is related to elastoplastic material modeling and the second set to structural model verification. Since model verification can be accomplished successfully, the developed model is well suited to provide prognoses of the loading of a gravel-buried steel pipe for rockfall scenarios that were not investigated experimentally.

INTRODUCTION

The rapid climate change in recent years leads to thawing of former permafrost regions in Alpine regions. A consequence of this evolution is the increased rockfall activity. This motivates a closer study of protection systems for transalpine infrastructure such as roads, railways, and pipelines.

Herein a gravel-buried steel pipe is considered. If a downfalling rock boulder impacts onto the overburden of the pipe, the kinetic energy of the rock boulder is transformed into other types of energy. Most of the impact energy is transformed such that inelastic deformations of the overburden are produced, i. e., an impact crater is formed. Other parts of the impact energy are transmitted through the gravel via elastoplastic waves to the buried pipe, which represents a rather stiff component of the statically overdetermined load-carrying system. Accordingly, the gravel acts as an energy-absorbing and load-distributing system.

This contribution deals with the development of an analysis tool that permits reliable predictions of the loading of a gravel-buried steel pipeline subjected to rockfall. The reliability test is based on two physically and statistically independent sets of experiments. Set ① is related to elastoplastic material modeling concerning the mechanical behavior of gravel and set ② to structural model verification.

ELASTOPLASTIC BEHAVIOR OF GRAVEL

Experimental set ① follows from the evaluation of a testing series for the elasticity of gravel as well as from the wealth of data on (triaxial) gravel strength published in the open literature. This data set is used for the identification of material parameters for gravel, i. e., of physical quantities attached to a "representative volume element" with a characteristic length scale of one to several decimeters. This identification is possible because the related experiments are characterized by homogeneous conditions, i. e., by the absence of spatial gradients of material parameters and loading conditions in the aforementioned length scales. Thus, the identified parameters are independent of structure-specific boundary conditions: they are valid for virtually all structures made of the investigated types of gravel.

Modeling of the material behavior of gravel

The elastoplastic Cap Model [1] suitably represents the rather complex material behavior of gravel, whereby the elastic domain follows the isotropic generalized Hooke's law. In the principal stress space, the elastic domain is bounded by three surfaces: (i) a tension cut-off, accounting for tensile failure, (ii) a Drucker-Prager surface, defining shear failure under pronounced deviatoric stress states, and (iii) an ellipsoidal cap, representing the hardening of the material associated with compaction. The direction of plastic flow is given by an associated flow rule. Consequently, loading in the cap mode leads to compaction whereas loading in the failure-surface mode or in the tension cut-off mode results in plastic volume dilatation. The material model involves nine material parameters: two referring to gravel elasticity, one to the failure of gravel under tensile loading, two corresponding to shear failure of gravel, two governing the hardening law for description of compaction of gravel, and two referring to the initial size and shape of the cap.

Identification of gravel elasticity

For identification of material parameters referring to gravel elasticity, dynamic tests were performed. Signals were produced by hitting the bucket of a dredger vertically onto the surface of wide-range-grained gravel. This led to propagation of both longitudinal and shear waves through the gravel. Their velocities were determined by means of accelerometer measurements. In the framework of the theory of wave propagation in elastoplastic solids, wave velocities obtained in repeated experiments allow for the calculation of a set of values of the two independent coefficients C_{1111} and C_{1212} of the isotropic fourth-order elasticity tensor $\mathbf{C}$. Assuming a scatter of the elastic properties of gravel according to a lognormal distribution, a statistical analysis yields estimates for the most probable elasticity parameters and respective 95%-confidence bounds.

Identification of the inelastic behavior of gravel

Identification of the parameters referring to shear failure of gravel is based on triaxial compression tests carried out on cylindrical specimens [3]. Remarkably, one set of material parameters characterizes shear failure of gravels of different grain shape, size, and distribution, mineral hardness, void ratio, and hydrostatic precompression satisfactorily ($r^2 = 0.995$).

Identification of material parameters describing compaction of gravel is again based on the tests reported in [3]. Apparently, grain shape, size, and distribution, mineral hardness, void ratio, and hydrostatic precompression do have a non-negligible influence on the compaction of gravel. However, rather small confinement pressures are of interest herein. This allows for unique identification of material parameters characterizing compaction of gravel.

The initial size and the shape of the cap are determined from constant volume tests, see [2]. The material parameter referring to tensile failure of gravel is set equal to a very small positive value in the numerical analysis.

Identification of the indentation resistance of gravel and loading assumptions for rockfall onto gravel

To model a gravel-buried pipeline subjected to rockfall, estimates of the penetration depth and the maximum impact-force of rock boulders are required as functions of the rock boulder mass, the height of fall, and the strength-like indentation resistance of the gravel. Therefore, impact tests were performed comprising heights of fall from 2 m to 19 m, and rock boulder masses from 4380 kg to 18260 kg.

The test results were evaluated by means of dimensionless formulae for the penetration depth of non-deformable projectiles onto concrete and soil targets. This analysis together with statistical methods allow for the determination of the most probable value, the 5 %-quantile, and the 95 %-quantile of the indentation resistance of gravel.

Finally, a model of the impact kinematics was deduced from experimental acceleration measurements. It allows for the estimation of the maximum impact-force arising from rockfall onto gravel. Given the wide range of dimensionless parameters for which the aforementioned dimensionless formulae were validated, extrapolations to rockfall events with heights of fall up to 100 m become possible.

DEVELOPMENT AND VERIFICATION OF A STRUCTURAL MODEL

The identified material parameters are used to simulate the structural behavior of a gravel-buried steel pipe subjected to rockfall. Thereby, the almost entirely inelastic indentation process of the rock boulder is not modeled in detail. Instead, the impact loads are considered in a simplified manner: the maximum impact force is applied to the surface of the Finite Element (FE) model, the overburden of which is reduced – with respect to the real overburden – by the indentation depth of the rock boulder at which the maximum impact force occurs. A quasi-static analysis is performed.

For verification of these simulations, an experiment on a real-scale gravel-buried steel pipe was designed, performed, and evaluated: A pipeline with an outer diameter d = 1016 mm and a wall thickness s = 11.13 mm, resting on a 40 cm thick layer of sand, was buried by wide-range-grained gravel in the middle of a trench of 3 m width such that the height of overburden was equal to 2 m. At selected positions of the pipe, the loading of the pipe steel was measured during the impact of a rock boulder with a mass of 18260 kg, dropped from a height of 18.85 m, by means of strain-gauges. The obtained data are collected into experimental set ②.

Simulation results obtained from the structural FE model based on the material parameters identified from experimental set ① are compared to the results of measurements from experimental set ②. In this way, experimental set ② allows for validation (i) whether the degree of sophistication of the material description based on the experimental set ① is sufficient for the assessment of the loading of a gravel-buried steel pipe subjected to rockfall, and (ii) whether the developed FE model is adequate. Since the simulation results compare well to independent experimental measurements, the developed model is well suited to provide prognoses of the loading of a gravel-buried steel pipe for rockfall scenarios that were not investigated experimentally.

It is shown that gravel may effectively serve as an energy-absorbing and load-distributing protection system for steel pipes subjected to moderate rockfall scenarios. However, it is not effective for rockfall events characterized by heavy rock boulders (such as investigated herein, e. g, m = 18260 kg) and heights of fall up to 100 m or even more. In order to provide a highly effective rockfall-protection system for a pipeline, the two tasks “damping of the impact” and “load distribution and carriage” must be performed by two separate structural elements. Such a system could consist, e. g., of (i) gravel acting as an energy-absorbing and, hence, impact-damping system, and (ii) additionally buried construction elements, made, e. g., of reinforced concrete acting as a structural component allowing for the distribution and for carrying of the impact load.

References

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