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ASSESSMENT OF PROTECTION SYSTEMS FOR GRAVEL-BURIED PIPELINES CONSIDERING IMPACT AND RECURRENT SHEAR LOADING CAUSED BY THERMAL DEFORMATIONS OF THE PIPE

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Summary. *Two safety topics in pipeline engineering are treated in this paper: (i) rockfall onto gravel-buried steel pipes and (ii) protection of the outer anti-corrosion coating of soil-covered steel pipelines. In both cases non-linear elasto-plastic Finite Element analyses provide insight into the structural behavior, as needed for the design of effective protection systems. For rockfall, a two-component protection system is recommended. It consists of an impact damping layer and of a buried load-distributing and load-carrying structure. As regards wear of the anti-corrosion coating, two well-established means of protection are considered to be most effective: (i) burying pipelines by sand and (ii) covering pipelines by (fiber-)reinforced concrete.*

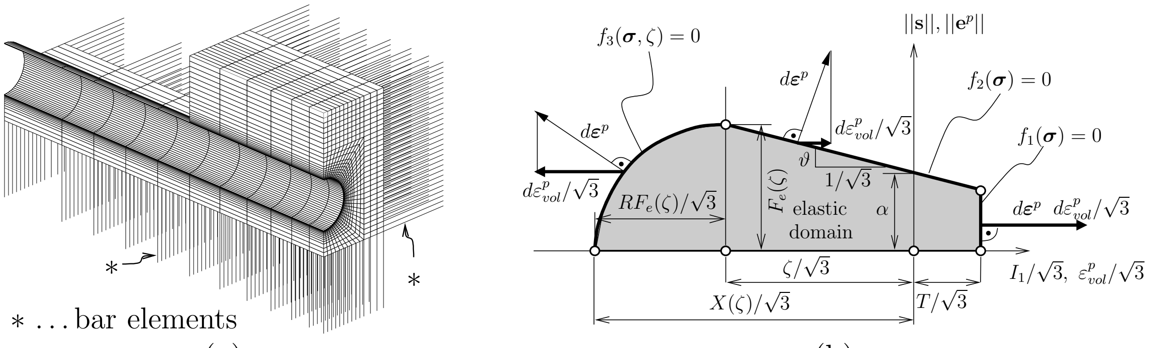
1 INTRODUCTION

Two safety topics in pipeline engineering are treated in this paper. The first one is related to impact of boulders onto gravel-buried steel pipes. The second one is protection of the outer anti-corrosion coating of soil-covered steel pipelines.

2 IMPACT OF BOULDERS ONTO GRAVEL-BURIED STEEL PIPES

Recent increase of rockfall activities in the European Alps has raised the need for designing impact protection systems for pipelines in Alpine valleys. In order to study the rockfall-induced loading of gravel-buried steel pipelines, a 3D, quasi-static, elasto-plastic Finite Element (FE) model (Fig. 1 (a)) has been developed. Estimates of maximum impact forces F and corresponding penetration depths w serve as input. They are obtained from dimensionless formulae which were originally derived for study of the impact of projectiles onto concrete [4]. In [7], these formulae were adopted for rockfall onto gravel based on a series of real-scale impact tests. The forces F are applied quasi-statically as surface loads onto the FE model, at a distance $(H - w)$ from the pipe, where H is the height of the gravel overburden. The material behavior of gravel is described by an elasto-plastic

Cap model [9, 2, 3]. In this model the elastic domain in the principal stress space is bounded by three surfaces (Fig. 1 (b)): (i) a tension cut-off, accounting for tensile failure, (ii) a Drucker-Prager surface, defining shear failure under distinctive deviatoric stress states, and (iii) an ellipsoidal cap, representing the hardening of the material associated with compaction. The related material parameters are identified from acoustic and static material tests on gravel [5]. The structural model is validated by comparing stresses in the pipe, predicted by the FEM, with stresses obtained from a real-scale structural experiment which is *independent* of the experiments used for identification of the material parameters representing input for the structural FE model [8]. Satisfactory FE predictions suggest the use of the FE model for estimation of the loading of the steel pipe for untested scenarios such as different heights of the overburden or different impact intensities (Fig. 2).



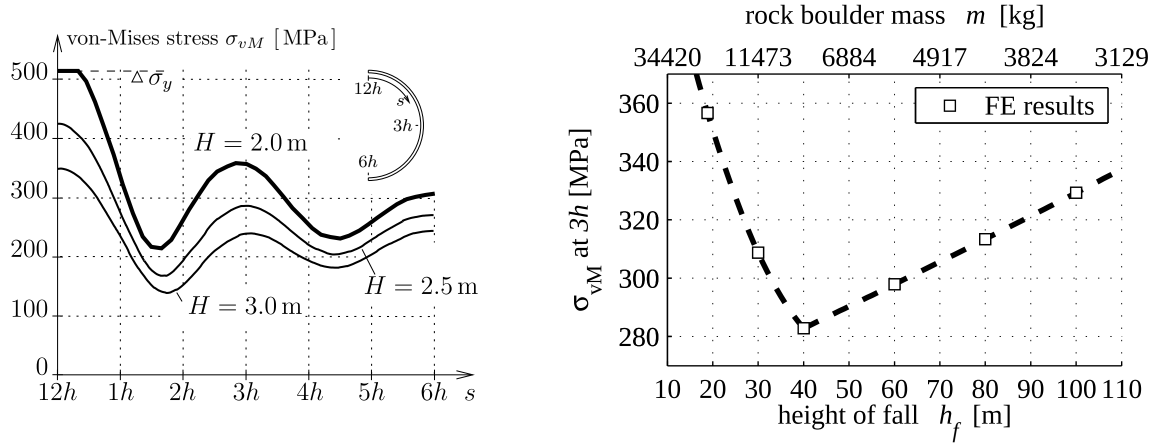
(a) (b)

Figure 1: (a) FE discretization used for the validation of the model: the mesh consists of 8634 three-dimensional brick elements and 426 bar elements simulating linear springs (Winkler foundation), (b) Cap model for gravel: elastic domain and direction of plastic flow, respectively, in a meridional plane of the principal stress and the plastic-strain space, respectively

1. Considering a specific rockfall scenario, i. e. a *given* boulder mass and a *given* height of fall, the loading of the pipe decreases less than linearly with increasing height of overburden (Fig. 1 (a)). Therefore, only a significant increase of the height of overburden can be regarded as an effective safety measure.

2. Considering a specific impact energy, the loading of the pipe is a non-monotonous function of the boulder mass and the height of fall, respectively (Fig. 2 (b)). This follows from the fact that completely indenting rock boulders cause a much more concentrated loading of a buried steel pipe than non-completely indenting boulders. Hence, considering completely indenting rock boulders in a series of constant-energy impacts, the risk of pipe damage increases with decreasing boulder mass and increasing height of fall.

These estimates highlight the potential and the limitations of gravel layers as a protection system for rockfall-endangered steel pipelines. They allow for recommendations for the



(a) (b)

Figure 2: Prognoses of von Mises stresses (a) along the inner surface of the pipe in the cross-section beneath the impact as a function of the height of overburden (boulder mass: 18260 kg, height of fall: 18.85 m), (b) at the $3h$ position as a function of the height of fall and the boulder mass, considering rockfall events with the impact energy $E_{kin} = 3380$ kJ (height of overburden: 2 m)

design of an improved rockfall protection system. The latter consists of two components: (i) gravel as an energy-absorbing and impact-damping system and (ii) a buried steel plate resting on walls made of concrete representing a load-carrying structural component. The performance of this advanced rockfall protection system is also assessed by means of 3D elasto-plastic FE-analyses. Respective results clearly point out the positive aspects of *redundant* safety systems protecting engineering structures [6].

3 PROTECTION OF THE OUTER ANTI-CORROSION COATING OF BURIED STEEL PIPELINES

Thermal deformations of oil and gas pipelines, related to recurrent temperature fluctuations of the transported fluid, cause shear loading of the coating, exerted by the adjacent material. Elasto-plastic FE analyses based on the Cap model (Fig. 1 (b)), simulating soil settlements near the pipe, allow to estimate the aforementioned shear loads. Considering a height of overburden equal to 1.5 m, these loads increase with decreasing diameter of the buried pipe. The effect of the shear loads on the anti-corrosion coating is assessed by Archard's wear law [1]. This suggests two effective strategies to prevent the anti-corrosion coating from damage: (i) reduction of the characteristic particle diameter of the adjacent material, e.g., embedding pipelines in sand, and (ii) increasing the hardness of a protective layer covering the anti-corrosion coating, e.g., covering pipelines by fiber-reinforced concrete.

4 CONCLUSIONS

Non-linear elasto-plastic Finite Element analyses have provided insight into two specific problems in pipeline engineering. Considering rockfall, it was shown that gravel layers have a limited capacity to serve as an effective protection system. The compliance of gravel, required for the damping of the impact, is opposed to the stiffness of the material needed for load distribution and for carrying the load. Therefore, a two-component protection system, consisting of an impact damping layer and of a buried load-distributing and load-carrying structure, is recommended. Considering wear of the anti-corrosion coating, two well-established means of protection are identified to be most effective: (i) burying pipelines by sand and (ii) covering pipelines by (fiber-)reinforced concrete.

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