DETERMINATION OF THE INDENTATION RESISTANCE OF GRAVEL AS THE BASIS FOR SAFETY PROGNOSES OF GRAVEL-BURIED STEEL PIPELINES SUBJECTED TO ROCKFALL

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ABSTRACT

This paper deals with rockfall-endangered pipelines made of steel, which are protected by an overburden consisting of densified wide-range-grained gravel. In order to define the minimum adequate height of the overburden, the load-carrying behavior of the hit structure is analyzed. For this purpose, the indentation resistance of gravel is identified in the framework of a hybrid analytical-experimental approach. In this way, both the penetration depth of downfalling rock boulders into densified gravel and the corresponding maximum impact force can be estimated. These impact characteristics serve as input for the numerical investigation of the load-carrying behavior of the hit structure. The development and verification of the respective Finite Element (FE) model will be also addressed. For this purpose, two additional physically and statistically independent sets of experiments are considered. The first set is related to elasto-plastic material behavior of gravel and the second set to structural model verification. Since model verification can be accomplished successfully, safety prognoses of gravel-buried steel pipelines subjected to rockfall become possible.

1 INTRODUCTION

The climate change in the last decades has resulted in thawing of former permafrost areas in the Austrian Alps. As a consequence, increased rockfall activity is observed, raising the need for the design of protection systems for exposed infrastructure. Herein, steel-pipelines are considered, protected by an overburden consisting of densified wide-range-grained gravel. The gravel layer serves as an energy-absorbing and load-distributing system. In order to define the minimum adequate height of the overburden, the load-carrying behavior of the hit structure must be analyzed. The requirements for such analyses include

1. loading assumptions, i. e., estimates of (i) the penetration depth of downfalling rock boulders into densified gravel and (ii) the corresponding maximum impact force,
2. modeling of the mechanical behavior of gravel and identification of the corresponding material parameters, and
3. verification of structural-model developments based on a physically and statistically independent set of experiments.

Section 2 deals with the identification of the indentation resistance of gravel, rendering loading prognoses of gravel-buried steel pipelines subjected to rockfall feasible. The development of a structural FE model is presented in section 3. The verification of this model is described briefly in section 4. Finally, prognoses of the loading of a gravel-buried steel pipe subjected to rockfall events that could not be investigated experimentally are presented and discussed in section 5.

2 IDENTIFICATION OF THE INDENTATION RESISTANCE OF GRAVEL: PREDICTION OF ROCKFALL PENETRATION DEPTH AND MAXIMUM IMPACT FORCE

The topic of the first experimental investigation – referred to as experimental set ① – were impact tests performed to determine the indentation characteristics of different rock boulders dropped onto gravel. These tests were performed with the help of a truck-mounted crane, limiting the rock-boulder mass and the height of fall to 20000 kg and 20 m, respectively. However, heights of fall that are considered by geologists as representative in real-life situations are in many cases by far larger than 20 m. Hence, the design of the tests was defined such that the obtained results allow for an extrapolation to rockfall scenarios that could not be investigated experimentally. The rockfall tests were performed on a layer of wide-range-grained gravel of 2 m thickness. The mass density of the material was equal to 1800 kg/m^3. Granite boulders of approximately cubic shape were dropped such that they impacted with a tip. Five tests were performed, comprising boulder masses of 10160 kg and 18260 kg, and heights of fall of approximately 2 m, 9 m, and 19 m. In order to analyze the experiments and to provide the desired extrapolation to rockfall events that could not be investigated experimentally, a dimensionless formula for estimation of penetration depths of non-deformable projectiles into concrete targets (see [Li and Chen, 2003] and references therein) is applied to the problem of rockfall onto gravel. The dimensionless formula reads:

$$\frac{X}{d} = \sqrt{\frac{1+k\pi/4N}{(1+I/N)}\,\frac{4k}{\pi} I} \qquad \text{for} \qquad \frac{X}{d} \leq k\,. \tag{1}$$

X denotes the penetration depth, d is the diameter of the projectile, N is a geometry function characterizing the sharpness of the impactor nose, I is referred to as impact function, and k is the dimensionless depth of a surface crater. For granite boulders of approximately cubic shape, with the volume V, impacting with a tip onto gravel, d, N, and k are obtained as [Pichler et al., 2004a]

$$d = 1.050\,\sqrt[3]{V}\,, \qquad N = 2.385\,, \qquad \text{and} \qquad k = 1.257\,. \tag{2}$$

The impact function I is defined as

$$I = \frac{m\,v_0^2}{d^3\,R}\,, \tag{3}$$

where m and v_0 denote the mass of the rock boulder and the impact velocity of the rock boulder, respectively. The mathematical relations (1)–(3) and the penetration depths measured from the performed rockfall experiments allow for back analysis of five values of the strength-like indentation resistance of gravel, R. Based on a statistical approach introducing a lognormal distribution, an estimate for the most probable value of R, denoted as $R_{50\%}$, and estimates of the 5%-quantile and the 95%-quantile of R are evaluated:

$$R_{50\%} = 9.22 \cdot 10^6\,Pa\,, \qquad R_{5\%} = 4.58 \cdot 10^6\,Pa\,, \quad \text{and} \quad R_{95\%} = 18.58 \cdot 10^6\,Pa\,. \tag{4}$$

Calculation of the quantiles is based on 95%-confidence intervals of the governing statistical parameters. The quantiles allow for a EUROCODE-conforming probability-based estimation of the indentation resistance of gravel. Penetration depth - height of fall diagrams based on the quantiles $R_{5\%}$ and $R_{95\%}$ (see Fig. 1) show wide bounds for the probability-based estimates of penetration depths. These bounds follow from the scatter of the material properties of gravel but also from the statistically small number of tests performed, namely, $n = 5$. Nevertheless, the model results based on the estimate of the most probable value of the indentation resistance, $R_{50\%}$, show very good agreement ($r^2 = 0.982$) with the experimentally obtained penetration depths (see Fig. 1). This fact underlines the usefulness of the presented approach. Taking this into account, and given the wide range of dimensionless parameters for which the employed dimensionless formula was validated in the framework of projectiles impacting onto concrete targets [Li and Chen, 2003], estimates of penetration depths into gravel caused by rock boulders with heights of fall up to $100\,m$ and, hence, by far larger than $20\,m$, become possible. Finally, a model of the impact kinematics is deduced from experimental acceleration measurements [Pichler et al., 2004a]. This model together with eqns (1)–(3) allows for estimation of the maximum impact force F as

$$\frac{m v_0^2}{F\,d} = \sqrt{\frac{1+k\pi/4N}{(1+I/N)}\,\frac{4k}{\pi}\,I} \qquad \text{for} \qquad \frac{X}{d} \leq k\,. \tag{5}$$

3 DEVELOPMENT OF A STRUCTURAL FINITE ELEMENT MODEL

3.1 Loading assumptions

The penetration depth and the maximum impact force are used as input data for an elasto-plastic FE model of the hit structure. For this analysis, a simplified representation of the loads arising from rockfall is chosen. The inelastic indentation process of the rock boulder is not modeled. Instead, the overburden of the FE model is chosen as the real overburden minus the penetration depth reached when the maximum impact force occurs. This penetration depth at maximum impact force is calculated with the model describing the impact kinematics [Pichler et al., 2004a]. The maximum impact force is applied to the surface of the FE model. The stress distribution resulting from the penetration of the tip of the rock boulder is computed by means of an axisymmetric linear-elastic FE model, comprising the gravel and the tip of the granite boulder – approximated as a conical indenter [Pichler et al., 2004c].

3.2 Further simplifications of the mode of analysis

Based on the results of a preliminary FE investigation, further simplifications are made: It was found that (i) elastic waves resulting from the impact propagate through the entire structure during a time span much shorter than the duration of the impact, and (ii) reflected waves do not contribute significantly to the loading of the pipe because they produce a loading which is much more diffuse than the concentrated loading resulting from the impact [Pichler et al., 2004c]. Therefore, quasi-

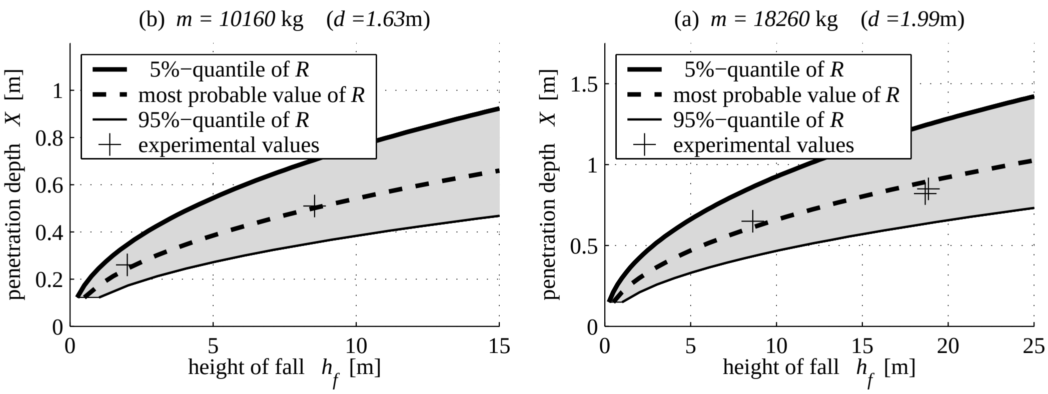

Figure 1: Comparison of model results (eqns (1)–(3) with $R = R_{5\%}$, $R = R_{50\%}$, $R = R_{95\%}$) and experimental results for (a) the $18260\,kg$ rock boulder and (b) the $10160\,kg$ rock boulder

static analyses are performed instead of dynamic analyses. Moreover, it was found that dead load results in stresses in the pipe, which are by two orders of magnitude smaller than the stresses caused by the investigated types of impact [Pichler et al., 2004c]. Hence, dead load is not taken into account.

3.3 Material modeling and parameter identification

For the description of the material behavior of steel, the classical von Mises elasto-plasticity theory is employed. The material parameters are taken from a respective inspection certificate, see [Pichler et al., 2004b].

Gravel is modeled by generalized Hooke's law and a Cap Model [Kropik, 1994]. Identification of the material parameters related to elasto-plastic material behavior of gravel is based on an additional set of experiments – referred to as experimental set ②. Measurements collected in experimental set ② comprise values of shockwave velocities from a testing series designed by the authors, as well as values from triaxial gravel-testing published in the open literature, see [Penumadu and Zhao, 1999] and references therein. This data set allows for identification of material parameters of gravel, including parameters related to gravel elasticity, shear failure of gravel, and compaction of gravel [Pichler et al., 2004b].

The material beside and beneath the trench which contains the buried steel pipe is represented by a Winkler foundation. It is modeled by bar elements representing linear springs.

4 VERIFICATION OF THE STRUCTURAL MODEL

For verification of the developed structural model, experiments on a real-scale gravel-buried steel pipe were designed, performed, and evaluated (experimental set ③): In particular, 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 $2\,m$. The material surrounding this trench was wet and, hence, rather soft clay. At selected positions of the pipe beneath the impact location, the deformation of the pipe steel was measured by means of strain-gauges during the impact of a rock boulder with a mass of $18260\,kg$, dropped from a height of $18.85\,m$.

This test is simulated by means of the developed structural FE model. Since material parameters of dense sand are comparable to the material parameters of the investigated type of wide-range-grained gravel (see, e.g., [Sawicki and Świdziński, 1998]), no distinction is made between sand and gravel [Pichler et al., 2004c]. The coefficient for the sub-grade reaction k_s characterizing the elastic foundation of the trench is set equal to $18\,MN/m^3$, which is the mean value of the interval $[12\,MN/m^3; 24\,MN/m^3]$ recommended for soft clay in [JDAAF, 1983]. Simulation results obtained from the structural FE model based on the loading assumptions deduced from experimental set ① and the material parameters identified from experimental set ② are compared to the measurements from experimental set ③. In this way, experimental set ③ allows to check whether the degree of sophistication of (i) the material description based on the experimental set ②, and of (ii) the developed 3D nonlinear FE model is sufficient for assessing the loading of a gravel-buried steel pipe subjected to rockfall, see Fig. 2.

In general, the simulated behavior of the steel pipe reflects the experimentally observed behavior of the tube satisfactorily, both qualitatively and quantitatively. Beneath the impact location, at $12h$ and $3h$, very good agreement between the numerical predictions and the experiments is observed, see the thick line and the circles in Fig. 2 (a). The largest relative error between the numerical simulation and the experiment is obtained at $6h$. There, the numerically predicted loading of the pipe is 49.5% larger than the experimentally obtained value. This deviation arises from the fact that the increase of the material parameters for gravel elasticity in case of compaction is not taken into account. However, in regions where the highest loading of the steel pipe occurs, the developed structural model yields satisfactory results. Consequently, the developed FE model possesses predictive capabilities, i. e., model verification is accomplished successfully.

5 PROGNOSES OF THE STRUCTURAL BEHAVIOR

The influence of different coefficients of sub-grade reaction on the loading of the pipe is studied (change of boundary conditions). First, k_s is set equal to $100\,MN/m^3$ as recommended for dense sand in [JDAAF, 1983]. Secondly, k_s is set equal to $500\,MN/m^3$ in order to investigate the limiting case of an almost rigid bedding. In these two simulations, the height of the overburden and the intensity of the impact remain those of the FE simulation performed for the verification of the model, see the previous section. In both cases that were investigated the maximum von Mises stress of the pipe, predicted by the FE simulation, does not reach the yield stress. An increase of k_s from $18\,MN/m^3$ to $100\,MN/m^3$ and $500\,MN/m^3$ results in a reduction of the loading of the pipe by approximately 25% and 30%, respectively.

The influence of different heights of overburden ($H = 2.5\,m$ and $H = 3.0\,m$) on the loading of the pipe is studied (change of structural dimensions). In these two simulations, the coefficient of sub-grade reaction and the intensity of the impact remain those of the FE simulation performed for the verification of the model, see the previous section. In both cases that were investigated the maximum von Mises stress of the pipe, predicted by the FE simulation, does not reach the yield stress. An increase of H from $2.0\,m$ to $2.5\,m$ and $3.5\,m$ results in a reduction of the loading by approximately 20% and 30%, respectively. The reduction of the von Mises stress at the 12h and at the 3h position is larger than the one at the 6h position. This indicates that the increased height of overburden results in a more distributed loading of the pipe.

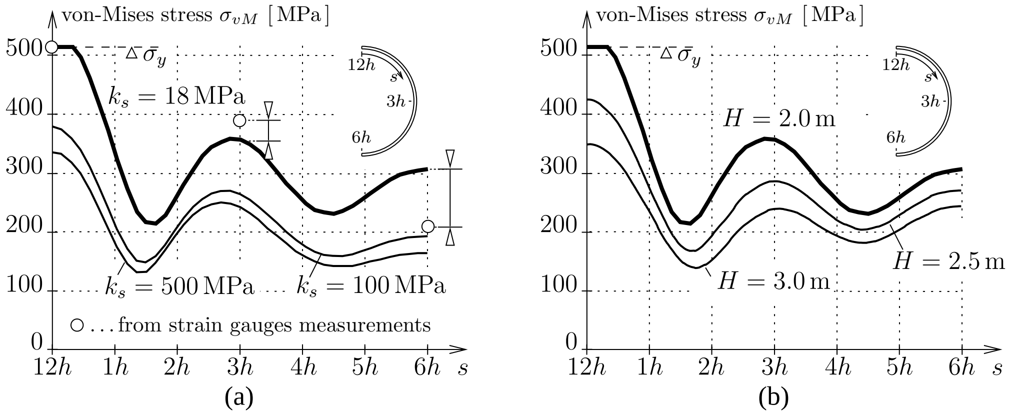

Figure 2: Distribution of the von Mises stress along the inner surface of the pipe in the cross-section beneath the impact for a rockfall event characterized by $m = 18260\,kg$ and $h_f = 18.85\,m$: values of von Mises stress calculated from experimental strain gauges measurements (○), results from the simulation of the performed experiment obtained by means of the structural FE model (thick lines), and prognoses of von-Mises stresses as a function of (a) the coefficient of subgrade reaction k_s, and (b) the height of overburden (thin lines)

6 CONCLUSIONS

It was 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 the most effective protection system. In this context it is noteworthy that a protection system for a steel pipe subjected to rockfall must satisfy two requirements: (i) damping of the impact in order to keep the forces arising from rockfall reasonably small, and (ii) load distribution and load-carrying capacity in order to reduce the loading of the steel pipe. In case of the investigated type of protection system, both tasks are performed by the gravel. The results presented prove that gravel has a certain capacity to fulfill the aforementioned requirements. However, the flexibility of gravel required for the damping of the impact is opposed to the stiffness of the material needed to meet the requirement of load distribution and of load-carrying capacity.

In order to further improve the effectiveness of a protection system for a steel pipe subjected to rockfall, the aforementioned two tasks could 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) buried construction elements, made, e. g., of reinforced concrete acting as a structural component allowing for the distribution and for carrying of the load.

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