

Article

Features of Modeling the Mechanical Response of Crushed Salt-Based Backfill Material in Potash Mines

Alexander A. Selikhov ^{1,*}, Maxim A. Karasev ¹, Vladislav V. Petrushin ¹, Ekaterina L. Romanova ², Anna V. Andreeva ¹, Vadim S. Biberin ³ and Egor S. Kudashov ³

¹ Department of Construction of Mining Enterprises and Underground Structures, Empress Catherine II St. Petersburg Mining University, 21st Line 2, 199106 St. Petersburg, Russia; karasev_ma@pers.spmi.ru (M.A.K.); petrushin_vv@pers.spmi.ru (V.V.P.); dementyeva_av@mail.ru (A.V.A.)

² Department of Industrial and Civil Engineering, Empress Catherine II St. Petersburg Mining University, 21st Line 2, 199106 St. Petersburg, Russia; romanova_el@pers.spmi.ru

³ Laboratory of Physical and Mechanical Properties and Rock Fracture of the Scientific Center for Geomechanics and Mining Problems, Empress Catherine II St. Petersburg Mining University, 21st Line 2, 199106 St. Petersburg, Russia; biberin_vs@pers.spmi.ru (V.S.B.); kudashov_es@pers.spmi.ru (E.S.K.)

* Correspondence: selikhov_aa@pers.spmi.ru; Tel.: +7-(921)-341-42-44

Abstract

The development of potash deposits under complex mining and geological conditions requires the implementation of efficient geotechnologies, including backfilling of mined-out voids. Preserving the water-protective strata and preventing mining-induced accidents are impossible without accurate prediction of the stress–strain state of the backfill mass. Traditional models, based on the Mohr–Coulomb criterion, are unable to properly describe physical and mechanical processes occurring in crushed salt rock, including the transition from dilatancy to compaction and nonlinear hardening. This requires the application of specialized models such as the SRP model. The aim of this study is to investigate the mechanical response of crushed salt rock backfill material under complex loading conditions and to calibrate the parameters of the SRP model in order to improve the accuracy of geomechanical calculations. The shape of the plastic flow surface in the deviatoric plane was established, including both shear and cap components. A nonlinear dependence of the friction angle on mean stress was identified and described by a logarithmic function. The law of plastic hardening was determined, and a non-associated plastic flow rule was confirmed in the shear domain. The calibrated SRP model allows for predicting the backfill mass behavior with high reliability, which is a necessary condition for substantiating the parameters of safe potash mining.

Keywords: crushed salt rock; laboratory investigation; plastic flow; plastic potential; hardening; shear failure; finite element method



Academic Editors: Haoyu Han,
Huimin Wang and Kai Tao

Received: 3 June 2026

Revised: 3 July 2026

Accepted: 7 July 2026

Published: 8 July 2026

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1. Introduction

The increasing consumption of potash fertilizers drives the mining industry toward complex geological conditions to extract lower-grade ores. Simultaneously, growing extraction volumes increase beneficiation waste, presenting significant geo-environmental challenges. The environmental impact can be reduced through integrated solutions that enable waste disposal in underground openings, solving the problem of waste utilization and space-saving of up-surface tailings dam facilities [1,2].

The most effective measure for protecting mines against flooding accidents and preventing mining-induced disasters is the backfilling of the goaf. The analysis of the potash

and salt mine closures established that controlling rock mass behavior through backfilling is a significant safety condition [3]. In this way, the reservation of the water-protective strata (WPS) is a priority task, and backfilling provides a reduction in deformations of the surrounding rock mass, thereby decreasing the risk of WPS integrity loss [4]. At the same time, the backfilling technology option should be based on a prediction of the geomechanical state of the rock mass under different mining systems [5], including longwall extraction, where the interaction between the backfill and the rock mass is especially crucial [6].

The backfill material selection is also an important aspect. Previous studies proved the efficiency of using binders based on calcium chloride [7]. It was also established that halite waste processing improves the strength properties of the backfilling [8]. The application of cementless mixtures based on water-soluble production-induced waste is also an advanced research direction. Backfilling based on this kind of recycled material is able to reduce the cost of mining operations while the required properties of the mass remain constant [9]. While designing, it is vital to consider backfill as a structural element of the mining system that redistributes loads [10].

The safety of mining operations is impossible without reliable prediction of the stress-strain state (SSS) of the rock mass. This requires accounting for the deformation properties of salt rock and time-dependent changes in the loads acting on interchamber pillars [11]. Under complex dynamic loading and seismic impact, special approaches are required for evaluating the stability of support systems and underground openings [12–14]. Current challenges also include the prediction of rock displacement around mine openings at great depths [15], as well as integrated forecasting of the SSS taking into account block structure and tectonic disturbances [16]. In some cases, for example, in permafrost construction, it is necessary to consider specific factors affecting the mechanical properties of rocks and foundation structures [17,18], which highlights the need to adapt geomechanical models to specific environmental conditions.

Modern forecasting methods increasingly rely on advanced digital technologies. In particular, machine learning methods allow stress and strain fields around interacting mine openings to be predicted with high accuracy [19]. Models with nonlinear yield surfaces improve the accuracy of simulating backfill mass stability [20]. Mathematical modeling of the backfill mass must also be built on its heterogeneity and the evolution of properties due to the passage of time [21].

The most challenging problem here remains to be the modeling of the reconsolidation (compaction) process of crushed salt rock itself. Fundamental studies in this field [22], as well as investigations into the properties of dynamically compacted salt [23], provide the basis for the development of valid constitutive models. Recent works pay particular attention to the effect of elevated temperature on microprocesses of deformation and reconsolidation [24], as well as to the thermophysical properties of consolidated salt, which vary with porosity and temperature [25,26].

To describe the behavior of backfill material accurately, specialized constitutive equations are required. A significant contribution in this area was made by studies conducted within the WIPP project, including model development [27], simulation of host rock deformation under backfilling conditions [28], and model verification against field data [29]. The implementation of viscoplastic models in modern software packages makes it possible to account for both volumetric and shear deformations [30], as well as for damage “healing” processes in salt rock [31]. Specialized constitutive models for crushed salt [32] allow prediction of long-term rock mass behavior; however, they require consideration of the effects of moisture and pressure [33], as well as coupled thermo-hydro-mechanical processes and halite solubility [34].

Recent studies emphasize that the degree of chamber backfilling affects the stability of interchamber pillars by changing their mode of deformation [35]. At the same time, the strength properties of salt rock itself vary significantly depending on the content of clayey-halite impurities [36]. Traditional models, such as the Mohr–Coulomb model, assume a linear dependence of shear strength on mean stress and a constant dilatancy angle, which may be inappropriate for crushed salt. This material is characterized by the following behavior: at low pressures, it exhibits the properties of a granular medium (shear and dilatancy); at high pressures, pore closure and hardening (compaction) occur.

To describe this transition properly, it is necessary to use models that include not only the shear part of the plastic flow surface (PFS), but also a cap component. Investigation of the shape of the plastic flow surface and plastic potential, as well as establishment of the functional dependence of the internal friction angle on mean stress, are crucial tasks. That will make it possible to consider the nonlinear strength gain of the backfill material during its compaction during mined-out space convergence. Without accurate calibration of the model parameters, it is impossible to predict reliably either backfill shrinkage or its supporting effect on pillars and the water-protective strata.

The aim of this study is to investigate the mechanical response of backfill material based on crushed salt rock under complex loading conditions and to calibrate the Soft Rock Plasticity (SRP) constitutive model to accurately describe its behavior.

2. Materials and Methods

The backfill material consisted of crushed salt rock from the Verkhnekamsk potash-magnesium salt deposit, with an average particle size of 0.88 mm. The particle size distribution was determined by sieving the material using a calibrated set of sieves with standard mesh sizes (0.16–0.32–0.63–1.25–2.5–5.0 mm) (Figure 1). It should be noted that the mechanical response of crushed salt, and consequently the calibrated SRP parameters (such as the hardening law and friction angle), are highly sensitive to the particle size distribution. A finer gradation typically leads to different initial compaction dynamics compared to coarser mixtures. Therefore, the parameters determined in this study are specific to this fine-grained grading (average size of 0.88 mm) and would require recalibration for backfill materials with significantly different fragmentation methods.

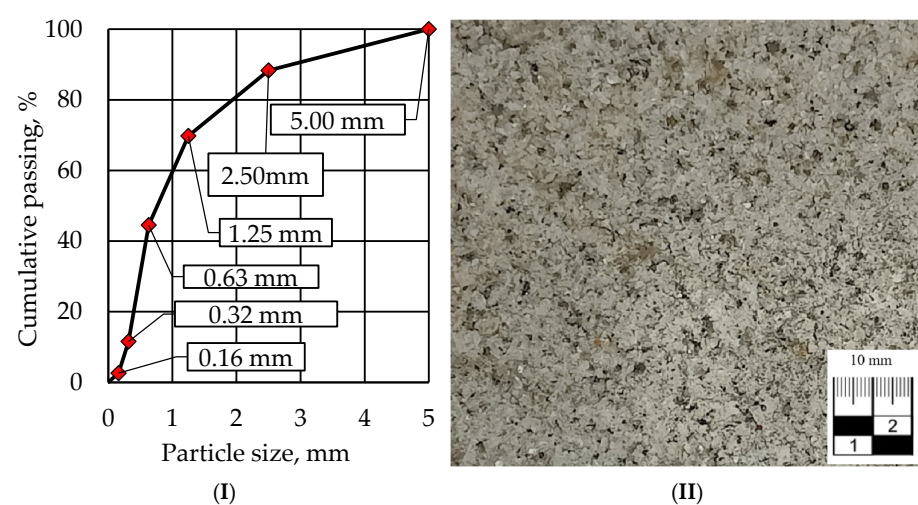


Figure 1. (I)—Grain size distribution curve. (II)—Photograph of crushed salt rock material [compiled by the authors].

The natural moisture content of the sampled material was approximately 1.57%. Before testing, the material was dried in an oven at 105 °C for 24 h to a constant mass, resulting

in a moisture content of nearly 0% to eliminate the influence of water on the mechanical response.

The test specimens, with a diameter of 60 mm and a height of 120 mm, were prepared by layer-by-layer compaction in a specialized cylindrical mold. The initial bulk density of the prepared specimens was 1400 kg/m^3 , which corresponds to an initial porosity of approximately 35% (assuming a true solid density of salt of 2160 kg/m^3). To ensure boundary sealing and prevent the penetration of hydraulic oil during triaxial testing, each specimen was encased in a double protective flexible waterproof jacket. All tests were conducted at a constant room temperature of 20°C .

To investigate the features of the mechanical response, the laboratory testing program summarized in Table 1 was developed.

Table 1. Laboratory testing program [compiled by the authors].

Test Trajectory	Purpose	Stress Levels/Ratios Tested	Amount of Specimens
hydrostatic compression	determination of hardening law	35 MPa	10
triaxial test according to modified Karman's scheme	determination of features of shear fracture	6 levels ($p = 0.75, 1, 2.5, 5, 10, 15 \text{ MPa}$)	36 (6 per level)
triaxial test according to classic Karman's scheme	determination of elastic modulus and Poisson's ratio	3 levels ($p = 5, 7, 10 \text{ MPa}$)	18 (6 per level)
triaxial test at constant σ_3/σ_1 ratio	determination of cap part of plastic flow surface	3 ratios (0.2, 0.35, 0.5)	18 (6 per level)

The selected loading paths reliably describe the plastic flow behavior of crushed salt rock. As shown in Table 1, multiple stress levels and ratios were investigated. To ensure statistical reliability under conditions of high structural heterogeneity of the backfill material, the sample size was set to six specimens for each target stress level (or for each stress ratio). For instance, the 36 specimens tested under the modified Karman scheme represent 6 parallel tests conducted at 6 distinct mean stress levels.

A sample size of six replicates allowed us to apply the Grubbs test to detect and reject outliers caused by random preparation defects. After outlier rejection, the actual sample size used for calculating the mean values was typically 4 to 5 valid specimens per stress level. Statistical analysis of the raw experimental data confirmed high reproducibility: the coefficient of variation (COV) for the ultimate deviatoric stress and volumetric strain across the tested groups ranged between 4% and 8%. For example, at a mean stress of $p = 5 \text{ MPa}$ under the modified Karman scheme, the ultimate deviatoric stress averaged 9.47 MPa with a standard deviation of 0.52 MPa ($\text{COV} = 5.5\%$). These statistical indicators substantiate the achievement of a 0.95 confidence level for the averaged characteristics, which is a critical condition for the high-quality calibration of the constitutive model.

The experiments were carried out using an MTS 815 (MTS Systems Corporation, Eden Prairie, MN, USA) servo-hydraulic testing machine (Figure 2) operating in a stress-controlled (soft) loading regime. The loading rate was kept constant for each test stage, varying from 0.05 to 0.5 MPa/min depending on the target mean stress level. Axial and lateral strains were measured continuously using high-precision linear variable differential transformers (LVDTs) mounted directly on the loading piston and the lateral surface of the specimen, respectively. The data acquisition system recorded the stress and strain parameters at a frequency of 1 Hz .



Figure 2. MTS 815 Servo-hydraulic testing machine [compiled by the authors].

The modification of the classic Karman scheme consists of reducing the hydraulic fluid pressure in the test chamber during deviatoric loading, which makes it possible to reach a pure shear mode of specimen failure. The investigated range of mean stress levels extended from 0.75 to 15 MPa for the Karman tests, whereas for hydrostatic compression and compression at a constant σ_3/σ_1 ratio, mean stress levels of 20 MPa and more were investigated.

3. Results and Discussion

The shape of the plastic flow surface in the deviatoric plane was established by the laboratory tests. The modified Karman scheme and the testing scheme with a constant ratio of principal normal stresses were used (Figures 3 and 4).

The plastic strain vectors plotted in Figures 3 and 4 were determined by calculating the increments of volumetric plastic strain (ϵ_{vol}^{pl}) and equivalent plastic strain (ϵ_{eq}^{pl}) at specific stages of loading. These increments were derived by evaluating the distance between two closely spaced data points as the specimen approached failure, and the resulting vectors were subsequently mapped onto the p-q stress plane.

In the shear part of the plastic flow surface (Figure 3), the sequence of vectors illustrates the evolution of the failure process: the intermediate vectors correspond to the pre-failure stages, while the final vectors (pointing steeply upwards) represent the exact moment

immediately preceding macroscopic shear failure. These final vectors form an acute angle with the yield surface, strictly confirming a non-associated plastic flow rule. Conversely, in the cap part of the PFS (Figure 4), the vectors are nearly orthogonal to the surface, which is consistent with an associated plastic flow rule for the initial compaction stage.

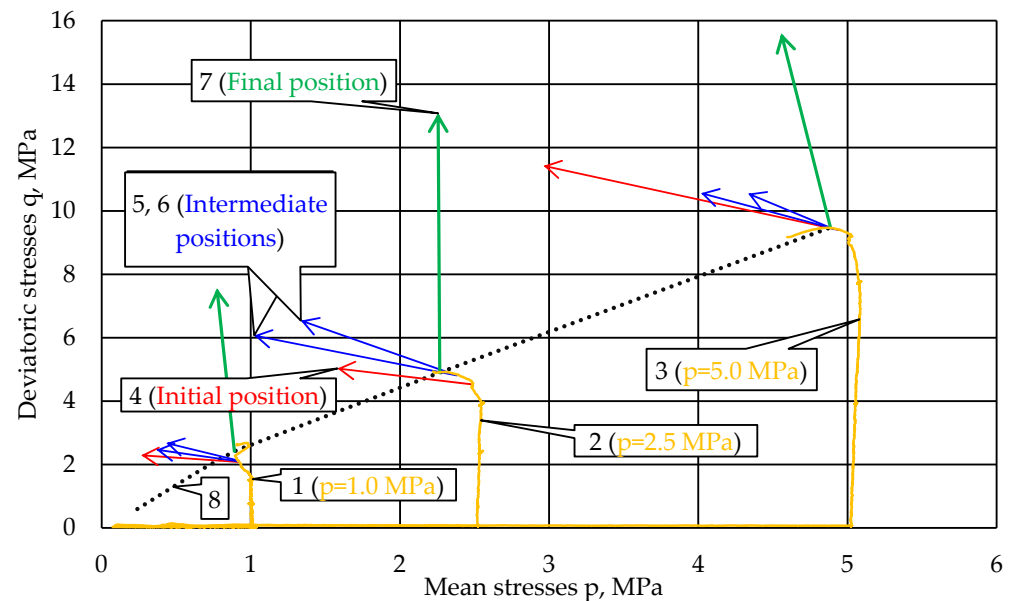


Figure 3. Development of vectors of volumetric plastic strain in the shear part of the plastic flow surface: 1—loading trajectory at $p = 1$ MPa; 2—loading trajectory at $p = 2.5$ MPa; 3—loading trajectory at $p = 5$ MPa; 4—initial position of the volumetric plastic strain vector; 5–6—intermediate positions of the volumetric plastic strain vectors; 7—final position of the volumetric plastic strain vector; 8—is the shear part of the plastic flow surface (colored arrows indicate the direction of plastic strain vectors) [compiled by the authors].

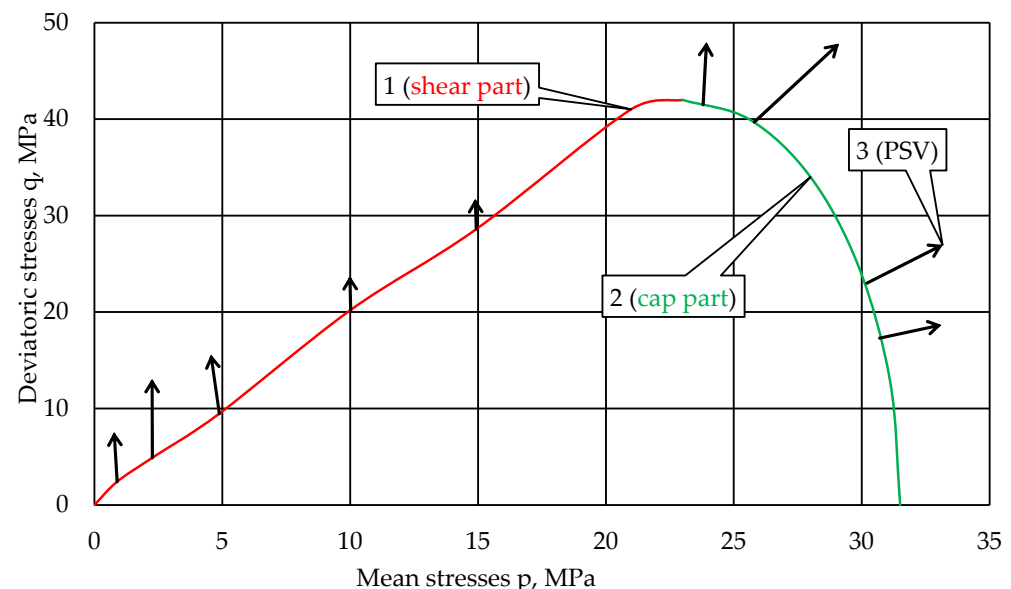


Figure 4. Shape of plastic yield surface: 1—shear part; 2—cap part; 3—plastic strain vector (PSV) (Black arrows indicate the direction of plastic strain vectors) [compiled by the authors].

The cap component of the PFS is described by an ellipse with a ratio of minor to major semi-axis of $R = 0.202$.

The tests according to the modified Karman scheme revealed nonlinear behavior of the backfill material under a shear-dominated failure mode. The inclination angle of the plastic

flow surface, β , within the mean stress, p , range from 0.75 to 15 MPa, varies according to the law described by Equation (1).

$$\beta = A \ln(p) + B, \quad (1)$$

where A —constant value, $A = -1.47$ degrees/MPa, B —constant value, $B = 76.45$ degrees.

It is important to note that Equation (1) is valid for the investigated mean stress range of 0.75 to 15 MPa. Because the logarithmic function becomes singular as $p \rightarrow 0$ ($\beta \rightarrow \infty$), it cannot be directly applied to the initial loose state of the backfill at near-zero confinement. Physically, the internal friction angle of the crushed salt reaches a maximum plateau at very low pressures. To avoid mathematical singularity and ensure computational stability in the numerical model, a lower-bound threshold was implemented: for $p \leq 0.75$ MPa, the angle β was capped at a constant maximum value of 77.0° .

Based on the hydrostatic compression tests, a plastic hardening law relating mean stress and volumetric plastic strain ε_{vol}^{pl} was established, with a coefficient of determination of $R^2 = 0.98$, which is expressed by Equation (2).

$$p = H_1 \varepsilon_{vol}^{pl\ 2} + H_2 \varepsilon_{vol}^{pl} + H_3, \quad (2)$$

where H_1 —constant value, $H_1 = 197.18$ MPa, H_2 —constant value, $H_2 = 13.05$ MPa, H_3 —constant value, $H_3 = 0.41$ MPa.

The elastic modulus ($E = 6.61$ GPa) and Poisson's ratio ($\nu = 0.13$) were determined from the unloading curves. These elastic constants were obtained from tests performed according to the classical Karman scheme at constant confining pressure levels of 5, 7, and 10 MPa.

To describe the full range of mechanical response features, the SRP model implemented in DSS SIMULIA Abaqus (Abaqus CAE 2020 (Dassault Systèmes, Johnston, RI, USA)) was found to be suitable. It allows the use of the associated plastic flow rule in the cap part of the plastic flow surface and a non-associated rule in the shear part. In addition, the model includes a hardening mechanism for crushed salt rock. Moreover, the software makes it possible to define a variable inclination angle of the shear part of the PFS as a function of mean stress.

Calibration (back-analysis) of the SRP model parameters was carried out using laboratory test data obtained from the modified Karman scheme, which included a hydrostatic compression stage followed by deviatoric loading (Figure 5). This complex loading path was specifically chosen for calibration because it simultaneously captures both the hydrostatic compaction and the deviatoric shear behavior across a wide range of mean stresses.

The numerical experiment reproduced the recorded axial load and hydraulic fluid pressure that created the triaxial stress state in the laboratory equipment. The model included both the specimen itself and the loading steel plates. The specimen-metal friction coefficient was determined experimentally as $\mu = 0.44$.

To ensure reproducibility and clarity, the physical meaning of each calibrated SRP model parameter is defined as follows:

- β : the friction angle of the yield surface in the p – q plane, which governs the shear strength, in degrees.
- ψ : the dilation angle defining the inclination of the plastic potential surface, which controls the volumetric expansion during shear, in degrees.
- n_y : the shape parameter of the yield surface in the deviatoric plane, controlling the curvature of the cap, dimensionless.
- p_t : the initial position of the yield surface in tension (initial cohesion intercept), MPa.

- f_0, f_1, α : the parameters controlling the shape of the yield surface in the π -plane (to account for the influence of the intermediate principal stress), dimensionless.

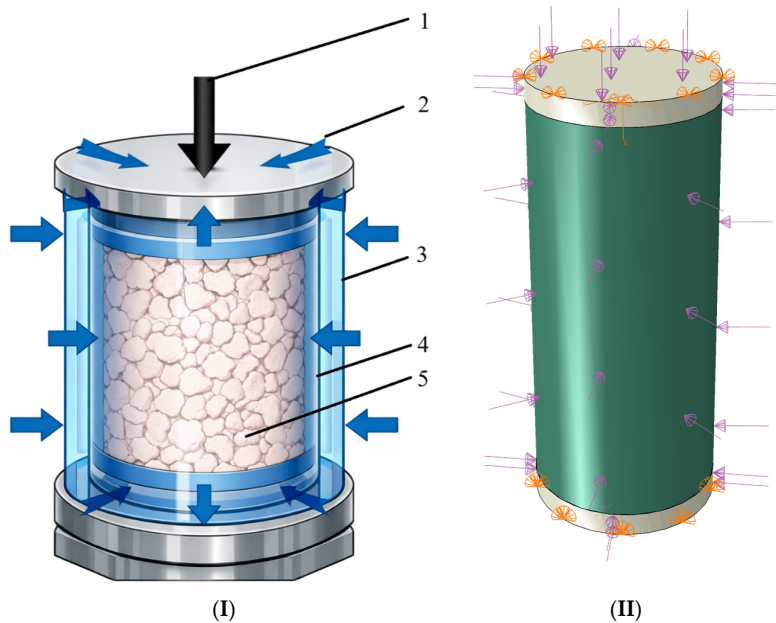


Figure 5. Numerical modeling ((I)—design scheme of the specimen; (II)—model assembly in Abaqus CAE software): 1—axial pressure σ_1 ; 2—lateral pressure (pressure of hydraulic fluid) σ_3 ; 3—external waterproofing soft shell; 4—internal waterproofing soft shell; 5—specimen material (blue arrows indicate lateral pressure, black arrows indicate axial pressure) [compiled by the authors].

The calibrated parameters for the crushed salt rock backfill are summarized in Table 2.

Table 2. SRP backfill material model parameters [compiled by the authors].

Friction Angle, β°	Dilation Angle, ψ	Cap Shape Parameter, n_y	Initial Tensile Yield, p_t , MPa	π -Plane Parameter, f_0	π -Plane Parameter, f_1	π -Plane Parameter, α
73–77.53	28–60.34	2.5	0	0.06	7×10^{-9}	0.5

To evaluate the quality and accuracy of the calibration process, a fit verification (back-analysis) was performed by comparing the numerical model outputs directly against the experimental datasets. While this represents a verification of the calibration fit rather than an independent predictive validation on a separate dataset, achieving a high degree of convergence across seven distinct mean stress levels (from 0.75 to 15 MPa) confirms that the selected SRP mathematical framework correctly captures the complex physical non-linearity of the crushed salt.

To quantitatively assess the model’s accuracy and analyze the residuals between the predicted and experimental lateral strains (ϵ_3), the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were calculated. As summarized in Table 3 and Figure 6, the error metrics are consistently low (with maximum MAE values not exceeding 0.0111), indicating a robust fit across the entire transition from initial compaction to dilation.

Table 3. Statistical metrics of the calibration fit quality for lateral strains (ϵ_3) at different mean stress levels [compiled by the authors].

Level of Pressure Along Test, MPa	0.75	1	2.5	5	10	15
The significance of the reliability values of the R^2 approximation	0.96	0.96	0.94	0.92	0.91	0.98
MAE	0.00356	0.00301	0.00437	0.0085	0.00491	0.00325
RMSE	0.00421	0.00352	0.00524	0.0111	0.00583	0.00434

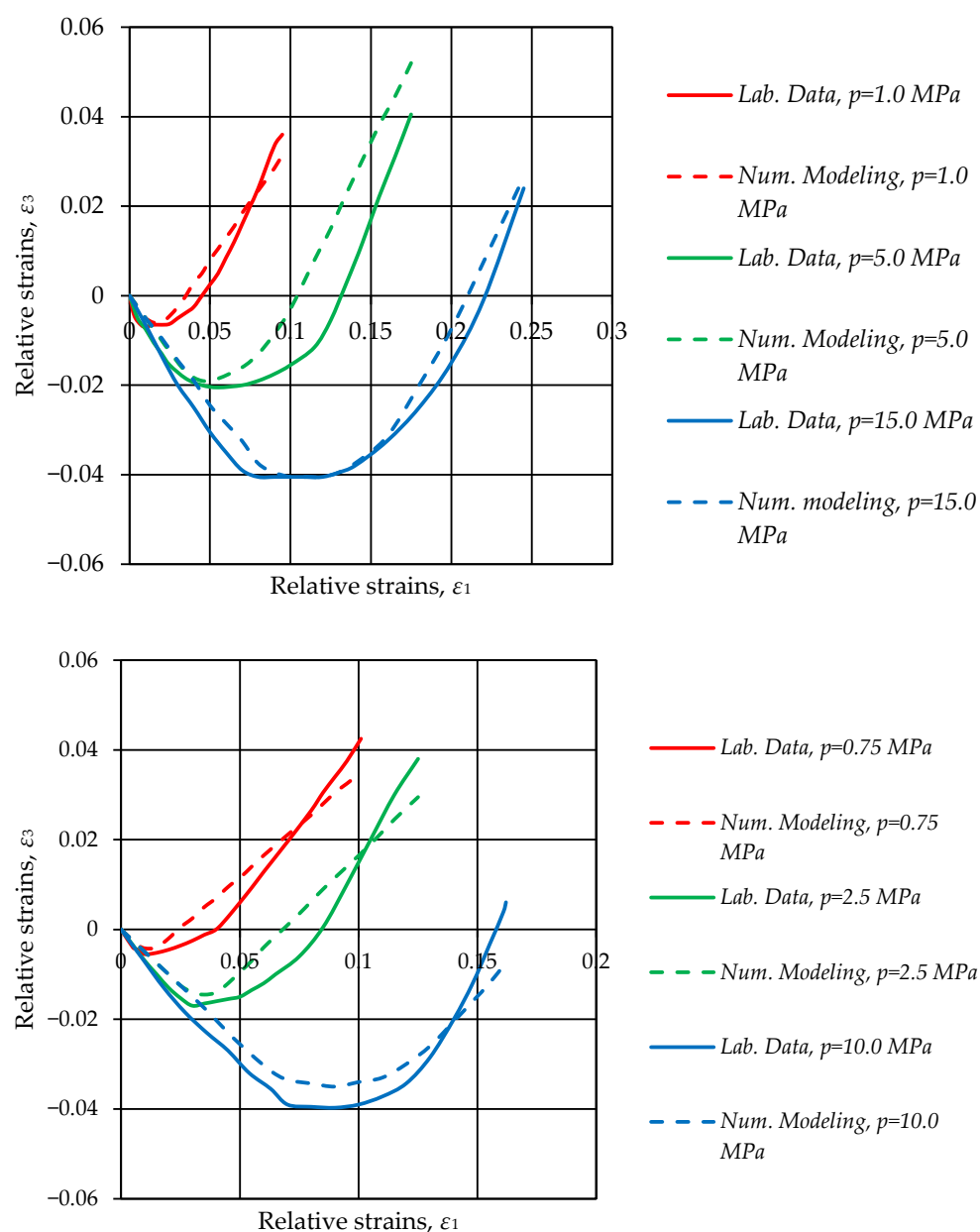


Figure 6. Comparison of the results of laboratory tests and numerical modeling [compiled by the authors].

The obtained SRP model parameters were compared with the results of fundamental and recent studies to verify the physical accuracy of the model.

First, the necessity of using a model with a cap component of the PFS with low eccentricity was confirmed. The analysis of the plastic deformation vectors obtained in [22]

while testing dynamically compacted salt shows a high ratio of volumetric deformations to shear deformations ($d\varepsilon_v^p/d\varepsilon_q^p \approx 0.7$). Under the condition of the associated flow law, this corresponds to the curvature range of the cap part of the PFS $R \in [0.18; 0.25]$. The value obtained in the present study, $R = 0.202$, indicates that the compaction mechanism is described correctly.

Second, the established logarithmic dependence of the inclination angle of the shear part of the PFS on mean stress specifies the approaches adopted in classical models [27,29]. Traditional models, such as the Mohr–Coulomb criterion, assume a constant internal friction angle and zero plastic volumetric strain under pure hydrostatic loading. However, our experimental data quantitatively invalidates these assumptions for crushed salt. Under purely hydrostatic compression, the material exhibited significant compaction, reaching a plastic volumetric strain (ε_{vol}^{pl}) of up to 0.36 at 35 MPa, which the standard Mohr–Coulomb model mathematically evaluates as zero.

Furthermore, using a constant friction angle causes severe predictive deviations. Data analysis showed that applying a constant average inclination angle results in a systematic error in shear strength prediction: an overestimation of 13–15% in the low-pressure range and an underestimation of 12–14% in the high-pressure range. The calibrated SRP model, which dynamically adjusts the inclination angle via Equation (1) and incorporates a cap component for compaction, effectively eliminates these fundamental physical contradictions.

A quantitative verification of the hardening law was also performed by comparing the results of this study with published data [35]. According to the referenced research, the oedometric modulus of elasticity for salt waste-based filling material is 14.42 MPa. In the present study, the linear hardening coefficient (H_2), which physically corresponds to the initial volumetric compression modulus, is 13.05 MPa; the discrepancy with the published oedometer modulus value is approximately 9.5%.

It should be emphasized that a direct one-to-one comparison of such parameters must be treated with caution. The mechanical response of crushed salt is highly sensitive to the initial bulk density, moisture content, and applied stress path. While the material in [35] and the present study share a similar genesis, minor variations in the initial compaction state and grain size distribution naturally lead to the observed 9.5% discrepancy. Nevertheless, this close agreement confirms the adequacy of the proposed description for the initial compaction stage of the backfill material.

Thus, the verified SRP model makes it possible to account for the physical nonlinearity of the deformation of backfill material based on crushed salt rock.

4. Conclusions

The above complex laboratory investigation of the mechanical response of backfill material based on crushed salt rock made it possible to identify the following key features: a nonlinear shear strength, a nonlinear plastic hardening law, and a non-associated plastic flow rule in the shear part of the plastic flow surface. At the same time, in the normal compaction zone (in the cap part of the plastic flow surface), the plastic flow rule is associated.

Based on the laboratory investigations performed, the SRP model was calibrated. Its functionality makes it possible to reproduce complex laboratory loading paths of the backfill material with an accuracy, taking into account the above-mentioned features of the mechanical response, with an average coefficient of determination of $R^2 = 0.94$. In contrast, classic models such as the Mohr–Coulomb model and Konstantinova’s model cannot reproduce such behavior. In addition, unlike the models of Callahan or of Olivella and Gens, the SRP model is implemented in widely used commercial software and does not require specific laboratory investigations for calibration.

Further work will be aimed at the consideration of the rheological properties of crushed salt rock. Additionally, a quantitative, large-scale numerical comparative analysis between the calibrated SRP model and traditional criteria (such as Mohr–Coulomb) at the excavation scale (e.g., interacting with interchamber pillars) is planned. This future research will assess the long-term influence of the backfill material on the stability of mining system elements and the surrounding rock mass.

Author Contributions: Conceptualization, M.A.K.; methodology, A.A.S.; software, V.V.P., E.L.R., A.V.A., V.S.B. and E.S.K.; validation, A.A.S.; formal analysis, A.A.S., V.V.P., E.L.R., A.V.A., V.S.B. and E.S.K.; investigation, A.A.S., V.V.P., E.L.R., A.V.A., V.S.B. and E.S.K.; data curation, A.A.S., V.V.P., E.L.R., A.V.A., V.S.B. and E.S.K.; writing—original draft preparation, A.A.S.; writing—review and editing, M.A.K., V.V.P., E.L.R., A.V.A., V.S.B. and E.S.K.; visualization, A.A.S.; supervision, M.A.K.; project administration, M.A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SRP	Soft rock plasticity
WPS	Water-protective strata
COV	Coefficient of variation
SSS	Stress–strain state
PFS	Plastic flow surface
PSV	Plastic strain vector
RMSE	Root mean square error
MAE	Mean absolute error

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