

16th International Benchmark Workshop on Numerical Analysis of Dams

THEME C: CALIBRATION AND PREDICTION OF THE ROCKFILL BEHAVIOR OF A 210M CFRD

Formulation text

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ICOLD Technical Committee A
THEME C: Calibration and prediction of the rockfill behavior of a 210m CFRD

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INTRODUCTION

The heights of the Concrete Faced Rockfill Dams (CFRD) have been steadily increasing throughout history. The last two decades have seen the construction of very high CFRDs. The few CFRDs close to or over 200m high have been put into operation in the last decades and some of them have experienced issues relating to cracks in the face slab and excessive leakage.

Historically, CFRDs are designed and built based mostly on empirical approaches. These recent incidents have exposed the limits of the empirical approach for designing CFRD and, since then, some more quantitative methods have been considered.

The Nam Ngum 3 HPP includes a 210m high CFRD, which is one of the highest of its kind in the world [1].

ARTELIA is acting as Owner's Engineer for Electricité du Laos. SinoHydro Corporation is the EPC Contractor.

The construction of the rockfill started in December 2017 and was concluded in June 2020. The reservoir filling is planned for April 2026.

The dam exhibits complex 3D and non-linear behavior. Thus, it is not possible to predict its behavior by means of simplified analytical formulas. It is necessary to develop predictive numerical models. These are initially defined based on laboratory test results and are generally calibrated along with the availability of the recorded monitoring data during construction.

The numerical simulation of the rockfill of the Nam Ngum 3 CFRD is proposed as the subject of the theme B of the 16th International Benchmark Workshop on Numerical Analysis of Dams.



Figure 1 – Picture of the Nam Ngum 3 CFRD (from June 2023)

1. SPECIFIC BEHAVIOR OF VERY HIGH CONCRETE FACE ROCKFILL DAMS

The construction of a very high CFRD is accompanied by uncertainties regarding deformation and settlement. Estimating this deformability is complex because it is affected by several interconnected phenomena, including:

- The scale effect i.e., the different behavior between the rockfill samples tested in laboratory and the actual rockfill to be constructed,
- The creep of rockfill i.e., its long-term behavior,
- The shape of the valley where the dam is constructed. A narrow valley may result in differential behavior between the center and the bank areas of the rockfill.

The scale effect is related to two main behaviors. The first one is that the rockfill grain size is too large to be tested in laboratory. Therefore, the laboratory tests which feed the initial predictive models are performed on reduced scale grain size. Yet, it has been observed that at least deformability is inversely proportional to grain size, resulting in overestimation of the relating parameters, especially for high stress conditions. The higher the dam, the higher the stresses on the grains, contributing to accentuate the effect of testing grains in smaller scale. Therefore the "scale" effect is related to both dam size and rockfill grain size.

The monitoring data of CFRD show that the settlement keeps increasing during several years after construction and impounding completion. This long-term behavior may be related to saturation and grain breakage. One possible explanation is that the change in saturation results in rearrangement of the grains and reduces the friction strength between them. The consequence is a continuous cycle of rearrangement, stress concentration and grain breakage.

When the valley where the dam is constructed is narrow, an apparent stiffness contrast between the center part and the bank parts of the rockfill adds to the above complex behavior.

The concrete face is very thin compared to the rockfill. Hence, it is under imposed deformation by that of the rockfill. If the concrete face is constructed before the long-term deformation of the rockfill has almost terminated, it may endure prestress. When the dam valley is narrow, the concrete may also endure a differential deformation. The two phenomena may result in extensive cracking in the absence of specific provisions and several authors attempted to define criteria relating the rockfill deformability and the valley shape with the acceptable behavior of CFRD's concrete face [2] [3]. However, the concrete face calculations are excluded of this Benchmark Workshop.

In any case, the reader can refer to ICOLD Bulletin B141 for some of the most recent practices in the design and construction of CFRDs [4].

2. PROVIDED DATA

The following data will be gradually made available:

- Laboratory tests results,
- Settlement monitoring data,
- The planning of the rockfill construction,
- 2D and 3D geometries:
  - 2D CAD Geometry,
  - 3D CAD Geometry + FE Mesh.
- Excel templates for the submittal of the results, including the description of the numerical model's main hypothesis.

2.1. 2D AND 3D GEOMETRIES

It is reminded that only the main rockfill of the dam is to be analyzed in the current Benchmark Workshop. More specifically, the concrete face is not considered to be constructed, nor the 1A and 1B materials.

The 2D geometry will be provided in a CAD format (.dxf) and will represent simplified rockfill contours as well as the outline of the 3B and 3C materials. Given their very low relative thickness, the 2A and 3A materials are considered to be part of the 3B material.

As shown in Figure 2, the 3C material was only used for a limited area and then 3B material was used. Only a height of 30m of 3C material were placed instead of the 150m initially designed.

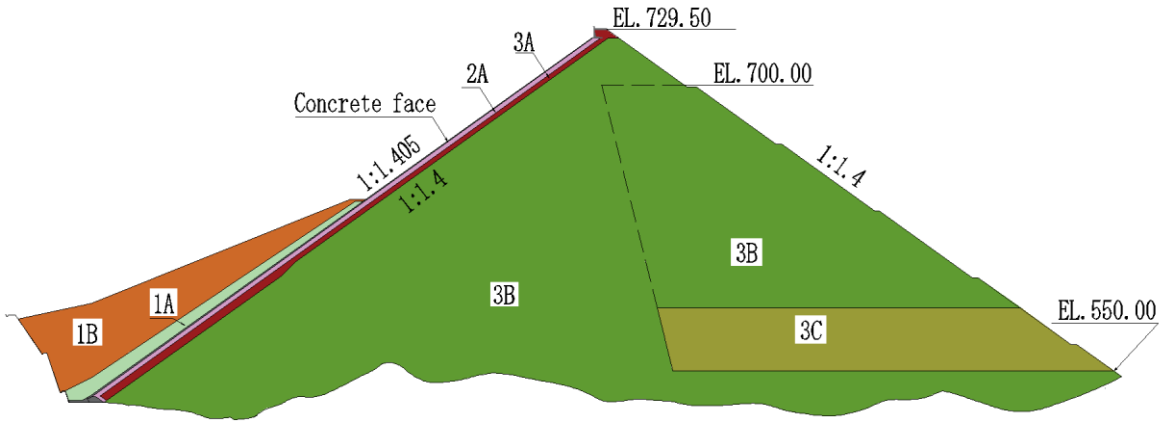


Figure 2 – Cross section of the highest dam profile

A simplified 3D model will also be provided in .dxf and STEP formats.

Finally, A 3D mesh and the relating data will be provided. The meshing layout will be a hybrid mesh including a vast majority of hexahedra but will also include to a lower extent tetrahedra and pyramids. The mesh will be compatible with ANSYS and will include three files giving:

- The node coordinates,
- The element coordinates,
- The element types.



Figure 3 – 3D geometry of the rockfill

2.2. LABORATORY TESTS

Triaxial and oedometer tests were conducted using materials that exhibited similar properties (void index, density, rock type, grain compressive strength) to those anticipated in the field. As previously mentioned, accommodating large rockfill diameters at the laboratory scale is currently unfeasible. To address this limitation, a gradation technique was employed to derive equivalent characteristics by scaling down the diameters.

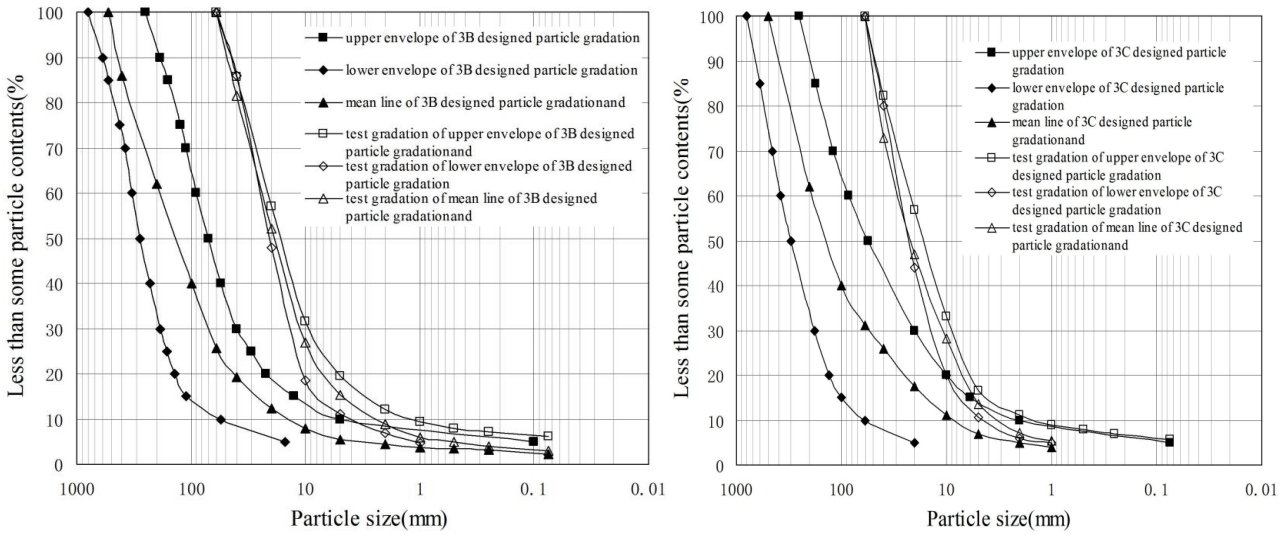
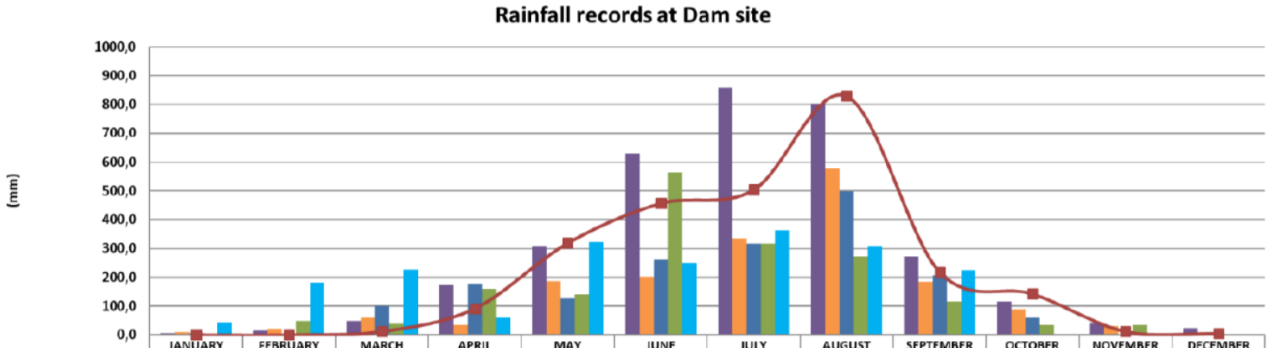


Figure 4 – Comparison between designed and tested 3B and 3C particle gradation

The rockfill is watered during compaction. Moreover, the dam site is located in a tropical area governed by monsoons with the rainy period lasting from April to October. Hence, the rockfill may endure at least a partially saturated state.



	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
2018	4,5	15,5	49,6	172,6	307,6	629,4	857,6	803,0	271,8	116,0	42,4	24,6
2019	10,8	22,2	59,0	34,8	186,8	201,6	335,0	580,0	185,0	88,4	29,8	0,0
2020	6,0	1,4	99,6	176,2	127,4	261,6	318,0	497,2	206,6	60,8	1,4	0,0
2021	0,0	47,8	39,0	160,2	141,4	563,4	317,8	271,6	117,0	35,4	35,4	0,0
2022	43,0	182,8	226,8	58,8	323,0	249,0	363,4	308,6	225,8	0,0	0,0	0,0
THEORETICAL (BD)	0	0	12	92	319	457	504	830	219	143	12	5

Figure 5 – Rainfall record from 2018 to 2022 at the dam site and as per Basic Design

Hence, when available, the laboratory tests results are provided under saturated or dry conditions. The Benchmark Workshop participants will choose whether the former or the latter are deemed more relevant.

2.2.1. Triaxial tests

These tests were conducted under different confining pressures with saturated material and drained conditions. The results are given in Appendix A.

Note that the volumetric strain cannot be retrieved from tests under dried conditions.

2.2.2. Oedometer tests

The oedometer tests for saturated and dried samples resulted in the axial pressure and void ratio relations given in Appendix A.

2.2.3. Creep tests

Creep tests have been carried out in order to assess the long-term behavior of the rockfill materials. The creep behavior of rockfill is a topic under development with several references in the literature. In the context of the Nam Ngum 3 project, the considered reference for the creep tests is Shen Zhujiang [5] [6].The tests are performed under triaxial conditions, with confining pressure (σ_3) from 500 kPa to 3000 kPa. For each confining pressure, four value of stress level (S_l) are applied and the history of axial (ε_a) and volumetric (ε_v) strain are collected.

Using these initial tests, it is possible to get the graphs of:

- The final volumetric strain (εvf) vs. the confining pressure (σ_3) ;
- The final volumetric strain (ε_{vf}) vs. the deviatoric stress (q) ;
- The final deviatoric strain (γf) vs. the stress level (S_l).

The stress level S_l relates the stress state to the Mohr-Coulomb criterion according to the following:

$$S_l = \left| \frac{(\sigma_1 - \sigma_3)}{(\sigma_1' - \sigma_3)} \right|$$

And illustrated in the following figure.

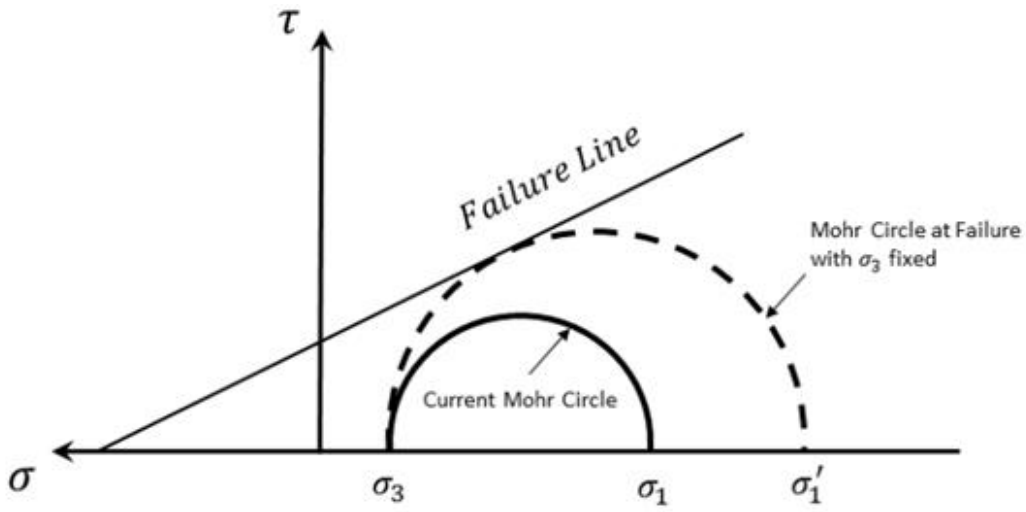


Figure 6– Illustration of the stress level "SI" parameters

The results of creep tests are given in Appendix A.

It should also be noted that a scale effect is also likely to exist between the laboratory tests and the actual rockfill for creep behavior. At least, a time scale effect is evident based on the laboratory test results.

2.2.4. Complementary information

The composition of the rockfill material is:

- 3B: 70% fresh gneiss (compression strength 120MPa, modulus of elasticity 67GPa) + 30% weak weathering silty sandstone (compression strength 20MPa, modulus of elasticity 3GPa).
- 3C: 90% weak weathering gneiss (compression strength 101MPa, rock modulus of elasticity 58.7GPa) + 10% strong weathering silty sandstone (compression strength 4MPa, rock modulus of elasticity 1GPa).

The participants are informed that for the creep tests, the samples are a mixture of 30% fresh gneiss + 70 % of weak weathered gneiss which is different from the actual 3B main rockfill material in place (70% fresh gneiss + 30% weak wathering silty sandstone). They are to consider the creep tests taking cognizance of this

The size of samples for the triaxial tests are the following: diameter D = 300 mm, height H = 700 mm.

The design dry density is 2200 kg/m3 for both 3B and 3C. The obtained dry and wet densities are around 2300 kg/m3 for both materials.

2.3. MONITORING DATA

2.3.1. Monitoring system setup

The dam rockfill includes monitoring networks of horizontal and vertical displacements. Three monitoring cross-sections are arranged in the bank-to-bank direction:

- Section 1: in the right bank (DL 0 + 165.00m);
- Section 2: the maximum height (DL 0 + 236.00m);
- Section 3: in the right bank (DL 0 + 330.00m).

For the purpose of the benchmark, only the maximum height cross-section is studied (Section 2).

To monitor vertical displacement in this cross-section, 5 water pipes are installed at different elevations for a total of 35 hydraulic settlement gauges, as shown here-below. The precise elevations and positions of each device will be provided later as tabular data.

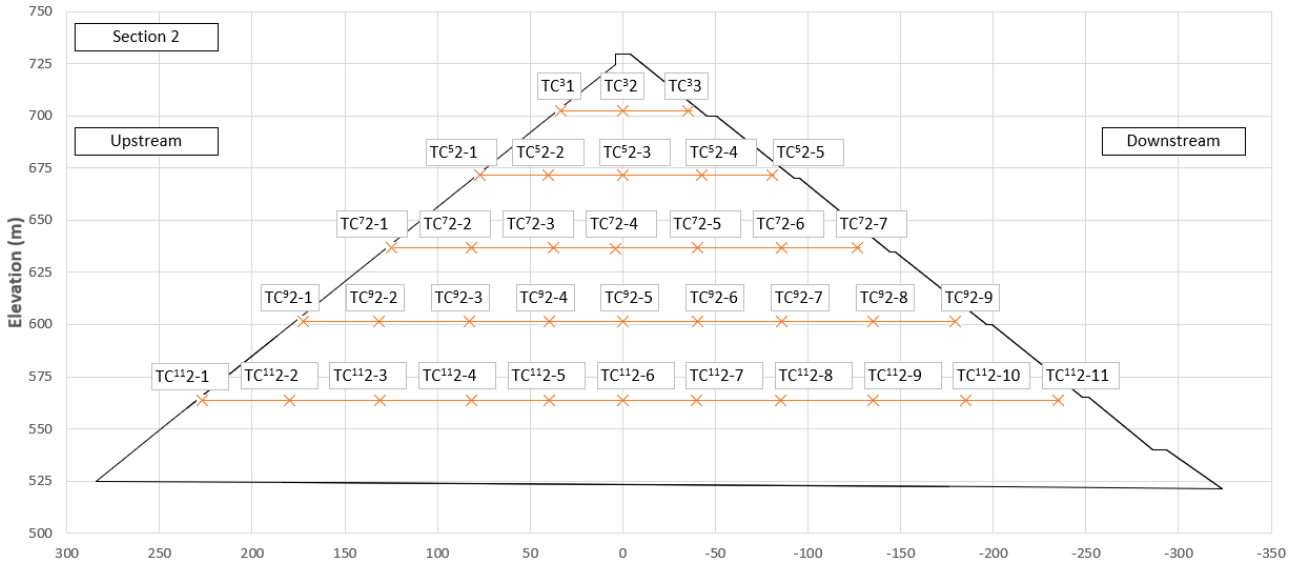


Figure 7– Illustration of the hydraulic settlement gauges positions

To monitor horizontal displacements in the same cross-section, 34 extensometers are installed as shown below.

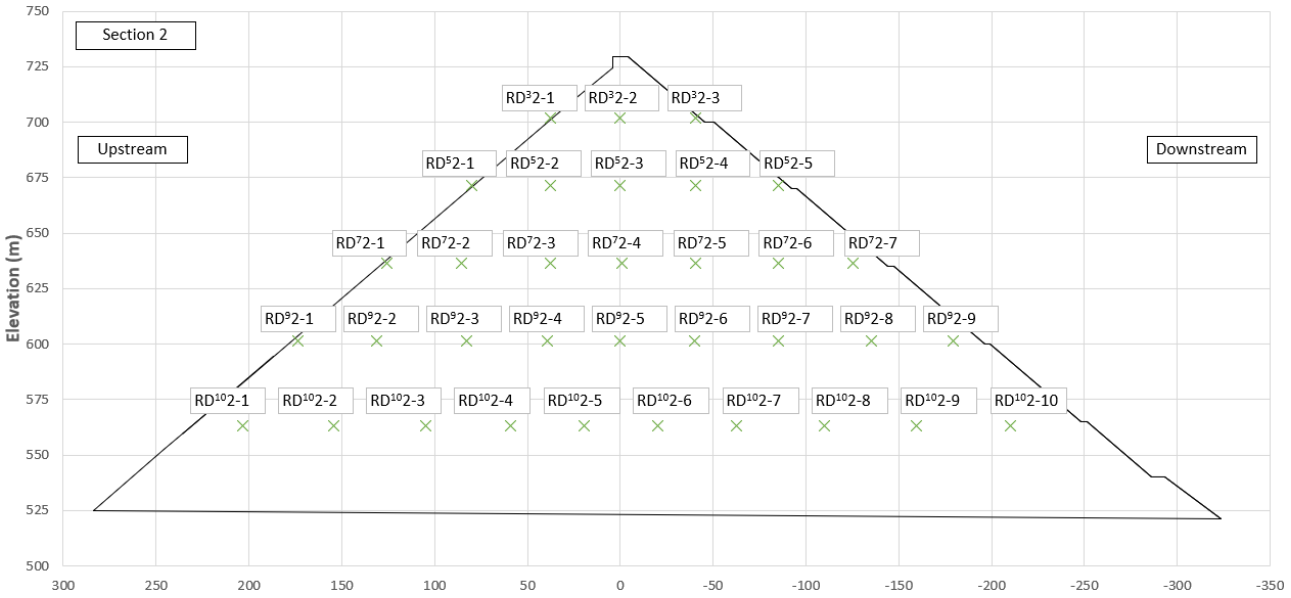


Figure 8– Illustration of the extensometers positions (horizontal displacement)

2.3.2. Monitoring limitations and applied correction

The monitoring of rockfill presents some limitations in the precision of the measures due to the large size of the boulders and large compaction energy. It is often necessary to install a transition material around the monitoring devices and to set a safety distance that the compactor must respect from the monitoring devices to avoid damages. These affect the

ability of the devices to measure the real rockfill behavior. Therefore, deviations of a few centimeters from the expected behavior can be tolerated.

In the case of Nam Ngum 3 dam, there was a delay between the installation of some devices and the zero-reading measure. For example, for the device TC7,2, the following delay is noticed:

- Device installation elevation: 636.70m,
- Installation date: 25th April 2019,
- Zero-reading date: 21st June 2019,
- Rockfill level at the zero-reading date: 661.50m,
- Omitted rockfill height: 24.8m (661.5-636.7).

Consequently, it is decided to apply a correction to the measures to compensate the omitted height. The correction is defined based on the measures following the initial gap and theoretical settlement estimations. The same correction is applied for all the devices of each elevation. Also, note that each instrument is independent of the others. Therefore, the correction applied to one instrument does not affect the instruments above it.

For the horizontal displacement, the correction varies along a given dam cross-section since the upstream devices move towards upstream, the downstream devices towards downstream and the central devices do not present important horizontal displacement. Therefore, the correction is made for each device.

Details of corrections are given in Appendix B.

In the following, unless otherwise indicated, all displacement measurements provided will take this correction into account.

2.3.3. Displacement data

Some measures at different elevations according to the rockfill construction progress are illustrated in the following chapters.

Displacements are given in centimeters.

2.3.3.1. Settlement (vertical displacement)

For instruments located in the middle of the section 2, the evolution of settlement as a function of the rockfill elevation is illustrated in Figure 9. It can be observed that settlement is still observed after reaching the rockfill top elevation. This late settlement under constant loading may be attributed to the effect of rockfill creep.

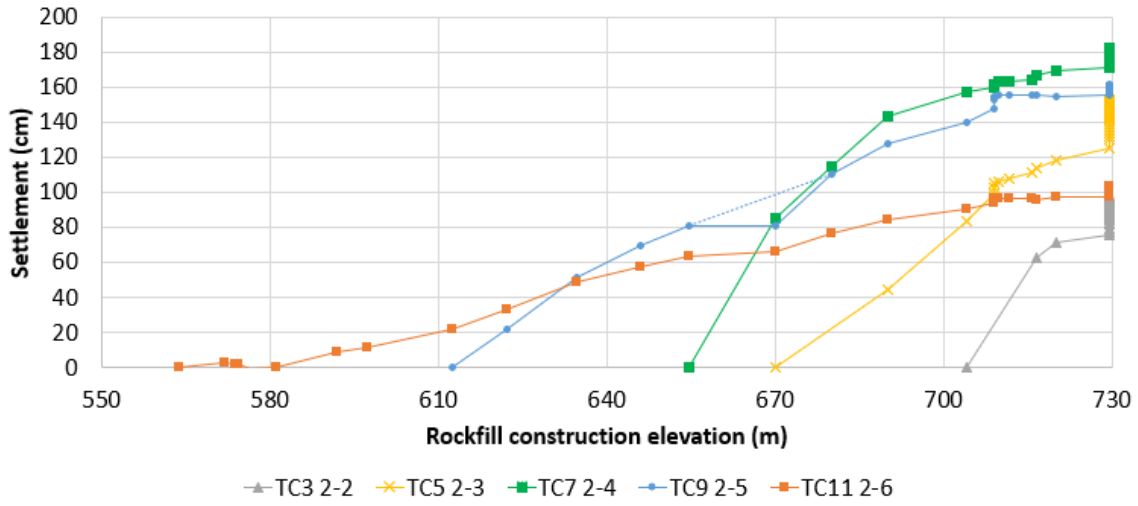


Figure 9– Corrected measured settlement as a function of the rockfill construction elevation.

The evolution of settlements over time are given hereafter.

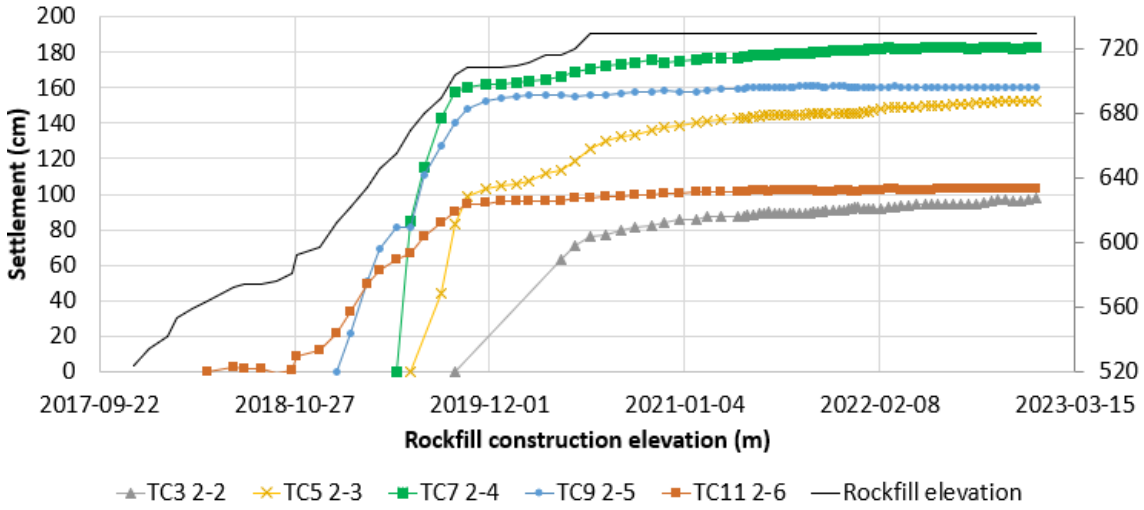


Figure 10 – Corrected measured settlement as a function of time

An illustration of the measures for all the monitoring positions at the end of the rockfill construction (continuous line) and the most recent long-term measures (dashed lines) is presented in Figure 11. The settlement is represented as a distance from the initial position.

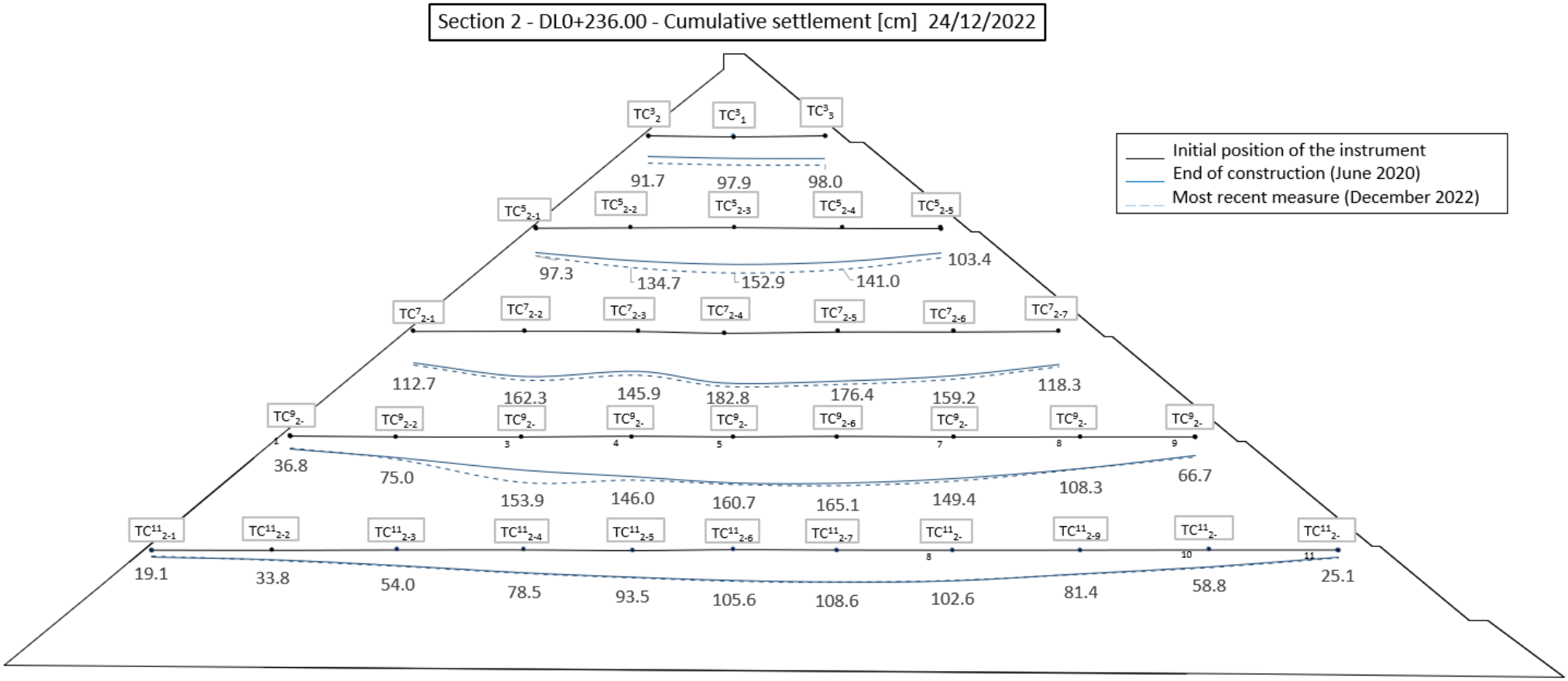


Figure 11 – Measured corrected settlement.

2.3.3.2. Horizontal displacements

The evolution of horizontal displacements is also provided as it is deemed to be also of value. It is up to the participants to consider them or not in the analysis.

The evolution of the horizontal displacement as a function of the rockfill elevation for the most upstream and most downstream measuring positions of each elevation is illustrated in Figure 12:

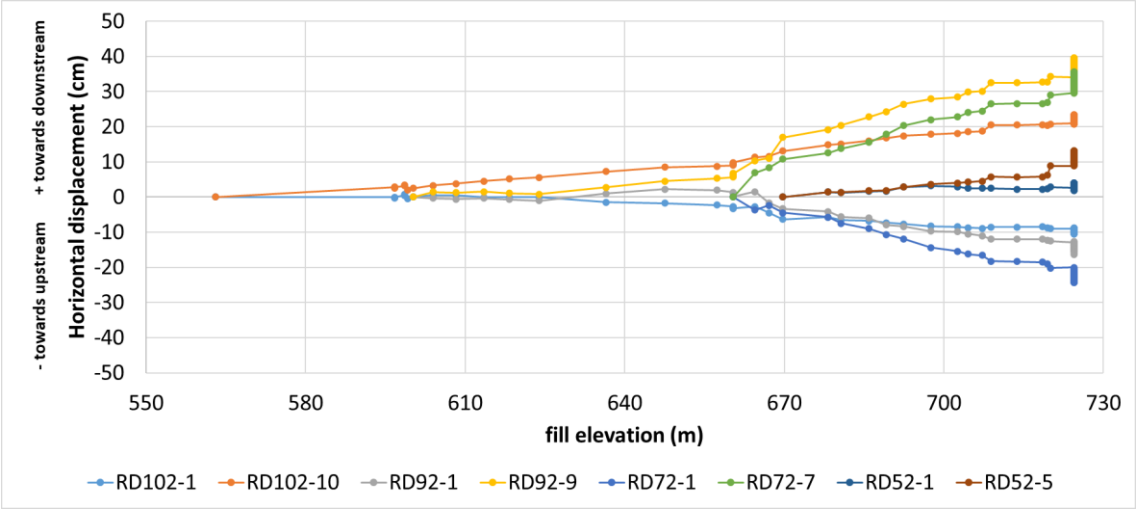


Figure 12 – Corrected measured horizontal displacement as a function of the rockfill construction elevation

The evolution of horizontal displacement over time is given hereafter.

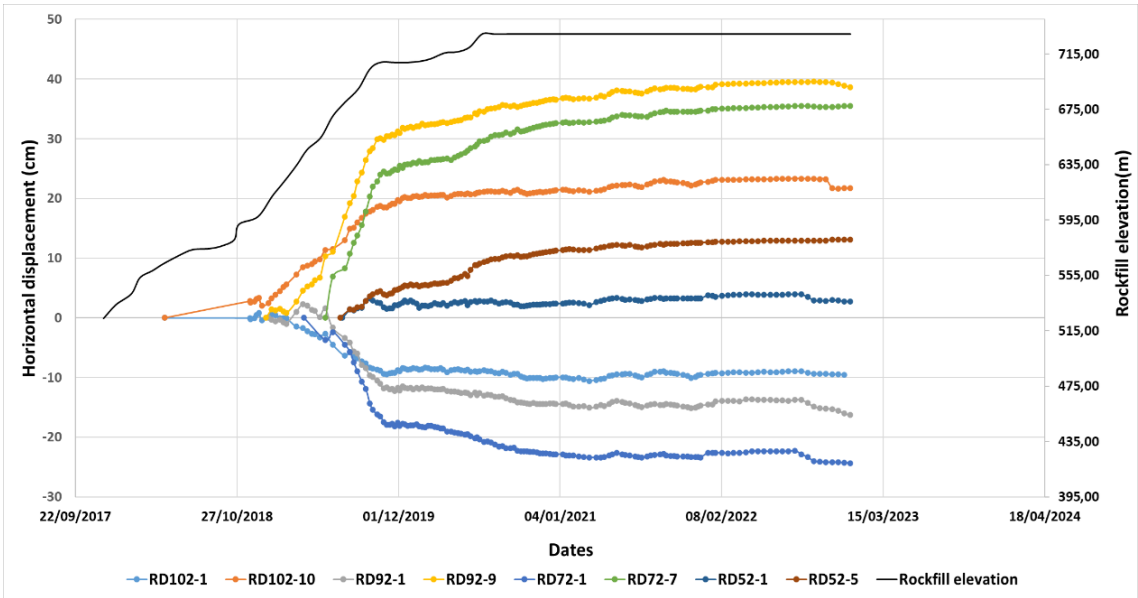


Figure 13 – Corrected measured horizontal displacement as a function of time

3. REQUESTED ANALYSES

The calculations are to be carried out focusing solely on the rockfill and its construction. Neither the concrete face nor the reservoir impounding is considered.

and will follow a progressive approach: the subsequent stages are of increasing complexity:

- A predictive analysis assuming that only the laboratory tests data are available,
- A calibration analysis, possibly starting from the above step, in order to consider the monitoring data and neglecting any creep behavior,
- A proposition from the participants of an approach to consider the scale effect from the comparison between the outcomes of the above two steps,
- A calibration analysis considering the monitoring data and including a creep mechanism within the material constitutive law.

For each step, calculations can be carried out using 2D or 3D models, but all 3D calculations are optional.

Table 1 – Types of analysis

CALCULATION STEPS	2D	3D
STEP 1: Predictive analysis of rockfill displacement during construction	Mandatory	Optional
STEP 2: Model recalibration based on monitoring data	Mandatory	Optional
STEP 3: Formulation of scale effect	Mandatory	Optional
STEP 4: Model recalibration including creep effect	Optional	Optional

3.1. STEP 1: PREDICTIVE ANALYSIS OF DISPLACEMENTS DURING CONSTRUCTION

It is suggested a simplified staged construction simulation of the rockfill considering that an entire elevation is constructed at once. Any eventual elevation offsets between different dam locations are suggested to be neglected as the offset was negligible in the case of Nam Ngum 3 dam. The construction layers are 80cm thick, but thicker layers can be considered in the numerical models at the discretion of the participants.

The compaction was made by 26t vibrating roller compactors with in average 16 passes for both 3B and 3C.

The participants are requested to define the material model parameters based on the laboratory test data.

Initially, the predictive model will use a Mohr-Coulomb elastic-perfectly-plastic constitutive model (MC).

Then, a Hardening Soil Model [7] (HSM), or any similar double-yield-surface constitutive law deemed relevant by the participant, will be used. At least, the participants are requested to use non-linear elastic model such as Duncan-Chang hyperbolic model [8]but the use of a more elaborate elastic-plastic model is encouraged.

For each modeling (MC and HSM or similar), the requested outputs are the following:

- Main modeling information (software, mesh, boundary conditions, …),

- Constitutive law parameters and material properties. The participants will be requested to simulate a triaxial test based on a single element model and the selected material parameters and plot the relating $q = f(\epsilon)$ and $\epsilon_v = f(\epsilon_a)$ curves. The same will be done for an oedometer test and it will be requested to plot $e = f(\sigma_v)$.
- Selected profiles of vertical and horizontal (upstream-downstream) displacements along the highest cross-section of the dam,
- Selected profiles of vertical and horizontal (upstream-downstream) stresses along the highest cross-section of the dam,
- Selected profiles of overconsolidation ratios along the highest cross-section of the dam. Each participant is invited to explain the rationale behind the choice of the initial preconsolidation stress considered in the model.

For this stage, the participants shall not consider any creep effect in the model.

For the 3D model, the used constitutive law shall only be of double-yield-surface type, or at least the Duncan-Chang hyperbolic model.

3.2. STEP 2: MODEL RECALIBRATION USING THE MONITORING DATA

For this step, participants will use the same constitutive laws as for the step 1 but are requested to recalibrate if necessary their parameters using the monitoring data provided in §2.3.

The same outputs as for step 1 are requested.

For this stage, the participants shall not consider any creep effect in the model.

For the 3D model, the used constitutive law shall only be of double-yield-surface type, or at least the Duncan-Chang hyperbolic model.

3.3. STEP 3: FORMULATION OF SCALE EFFECT

To assess the scale effect, it is requested to conduct a comparative analysis of results from the two previous calculation steps and therefore develop an approach for considering scale effect of rockfill materials in numerical deformation analysis of the participants judge that there is any to be considered.

This step aims to take into account the differences of deformability (and possibly strength) properties of rockfill material between in situ and laboratory conditions in the deformation analysis. The developed method shall be based on the results obtained from step 1 and 2 and is not expected to request any numerical analysis but rather a theoretical development.

The participants are consequently requested to elaborate on an approach to account for this scale effect in the numerical analysis if they judge that aspect to be considered.

The formulation team have used the approach described in [9] to consider the scale effect in the case of Nam Ngum 3 dam but the participants are free to propose any approach of their own.

3.4. STEP 4: MODEL RECALIBRATION INCLUDING CREEP EFFECT

As highlighted in chapter 2.3.3, there are residual settlement and horizontal displacements that take place after the rockfill construction i.e., under constant load (Figure 10 and Figure 12).

The main objective of this step is to consider a creep model within the constitutive laws of the materials. There are two options:

- Activate the creep model only to calibrate the measured displacements between the end of the construction (June 2020) and the most recent measures (December 2022), or

- Activate the creep model as early as the start of the construction up to December 2022 as there appears to be some evidence that creep is concomitant to the construction.

The requested outputs are:

- A description of the creep constitutive law and the relating parameters. A development relating to the choice and the relevance of the constitutive law,
- Selected profiles of vertical and horizontal (upstream-downstream) displacements along the highest cross-section of the dam,
- Selected profiles of vertical and horizontal (upstream-downstream) stresses along the highest cross-section of the dam,
- Selected profiles of overconsolidation ratios along the highest cross-section of the dam. Each participant is invited to explain the rationale behind the choice of the initial preconsolidation stress considered in the model.

3.5. EXPECTED TIME FOR EACH STEP

Table 2– Time estimation

Calculation steps	2D (days)	3D (days)
STEP 1: Predictive analysis of rockfill displacement during construction	8	10*
STEP 2: Model recalibration based on monitoring data	8	12*
STEP 3: Formulation of scale effect	2	3*
STEP 4: Model recalibration including creep effect	8*	10*
Total	26	35*

*related to an optional task

4. EXPECTED OUTCOMES

In addition, the participants are requested to write a scientific paper discussing one or more of the following topics, or any other related to the modeling work that they have carried out:

- The ability of the constitutive laws in simulating with a good accuracy the displacement patterns of the rockfill;
- The existence of a scale effect when comparing laboratory tested small scale rockfill to the actual large scale rockfill;
- The necessity of 3D model for CFRD constructed in narrow valleys;
- The relevance of considering creep models in simulating the stress-strain behavior of very high rockfill dams.

5. REFERENCES

[1] X. DUCOS, Q. BERCHER, G. OUBRY, F. BROUSSET et K. PHET-ASA, «Construction challenges of a high CFRD dam for the Nam Ngum 3 hydro plant,» *ASIA 2020*, 2020.

[2] N. PINTO et P. MARQUES, «Estimating the maximum face deflection in CFRDs,» *Hydropower & Dams,* 1998.

[3] E. FROSSARD et C. NIETO, «Design and construction of Mazar CFRD (Ecuador) - Behavior in service,» *ICOLD - 25th Congress of Large Dams*, Stavanger, 2015.

[4] ICOLD, «Bulletin 141 - Concrete Face Rockfill Dams - Concepts for design and construction,» 2010.

[5] Z. SHEN et Y. ZUO, «Study on rehology characteristics of rockfill,» *Proc of the 6th China soil mechnaics and foundation engineering Conference*, 1991.

[6] Z. SHEN et K. ZHAO, «Back analysis of creep deformation of rockfill dams,» *Journal of Hydraulic Engineering*, 1998.

[7] T. SCHANZ, P. VERMEER et P. BONNIER, «Formulation and verification of the Hardening-Soil Model,» *Beyond 2000 in Computational*, Amsterdam, 1999.

[8] J. DUNCAN et C. CHANG, «Nonlinear analysis of stress and strain in soils,» *Journal of Soil Mechanics & Foundations Div.,* 1970.

[9] E. FROSSARD, W. HU, C. DANO et H. PY, «Rockfill shear strength evaluation : a rational method based on size effects,» *Géotechnique 62*, 2012.

APPENDIX A
LABORATORY TESTS

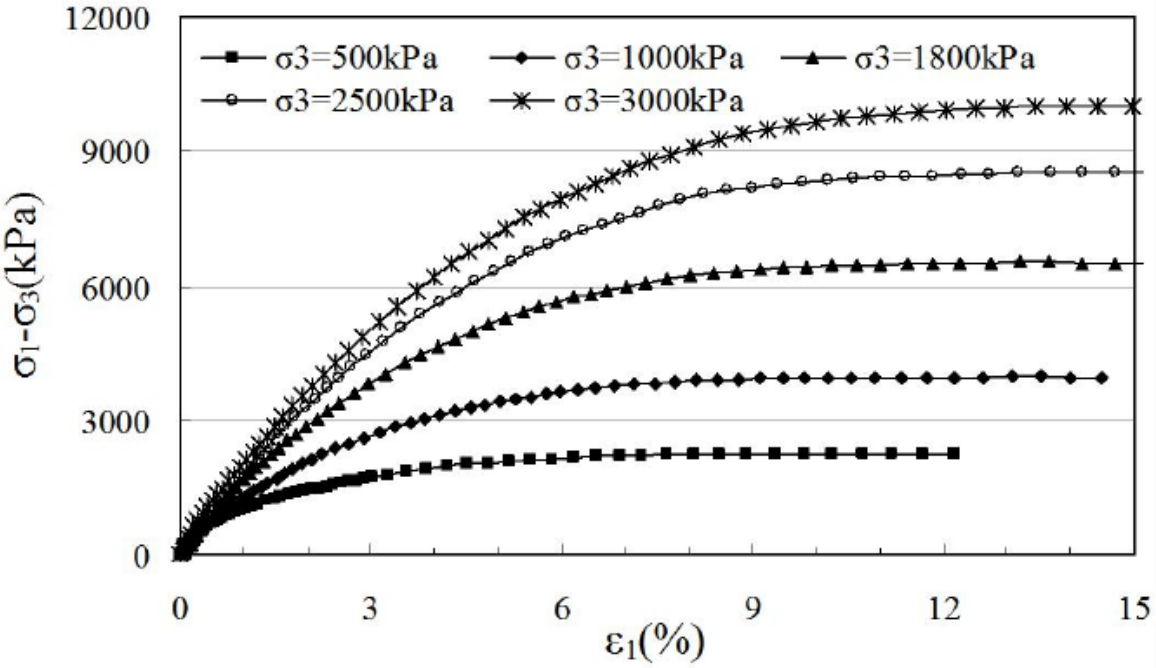


Figure 14 – Triaxial test: deviatoric stress (q) vs. axial strain (*ε*1) for 3B – Saturated

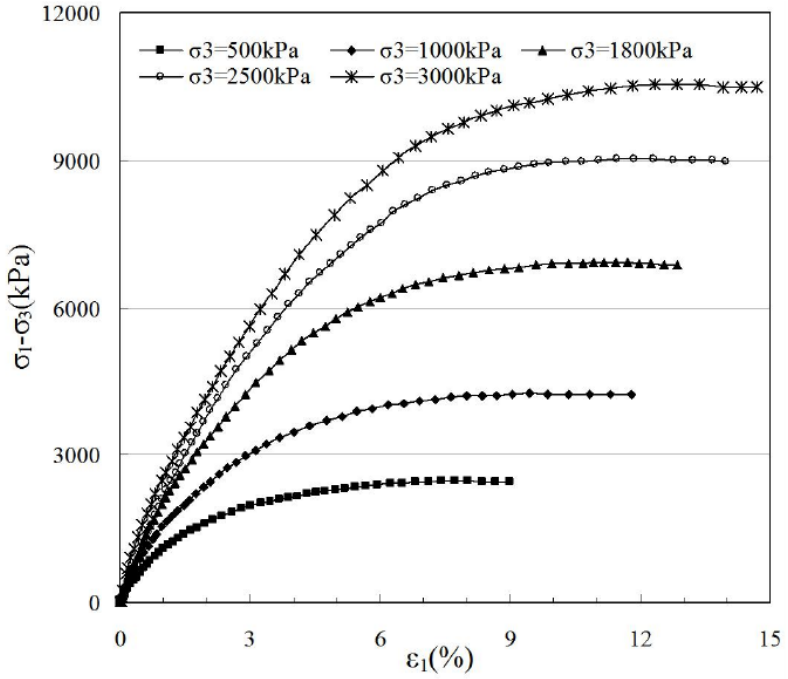


Figure 15– Triaxial test: deviatoric stress (q) vs. axial strain (*ε*1) for 3B – Dried

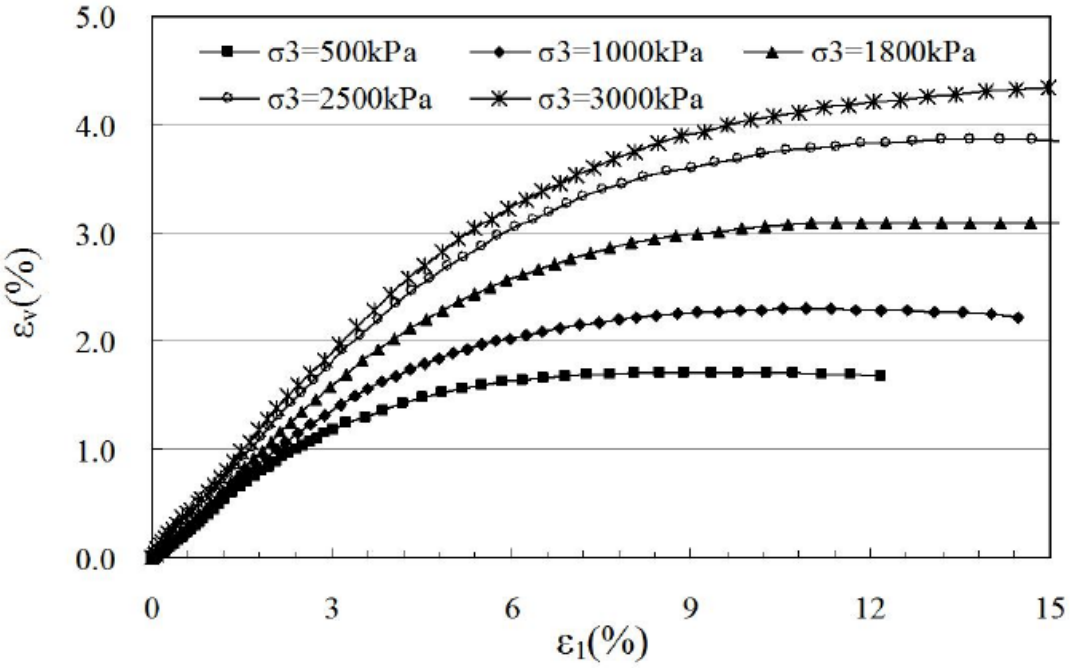


Figure 16 – Triaxial test: volumetric strain (*ε*v) vs. axial strain (*ε*1) for 3B – Saturated

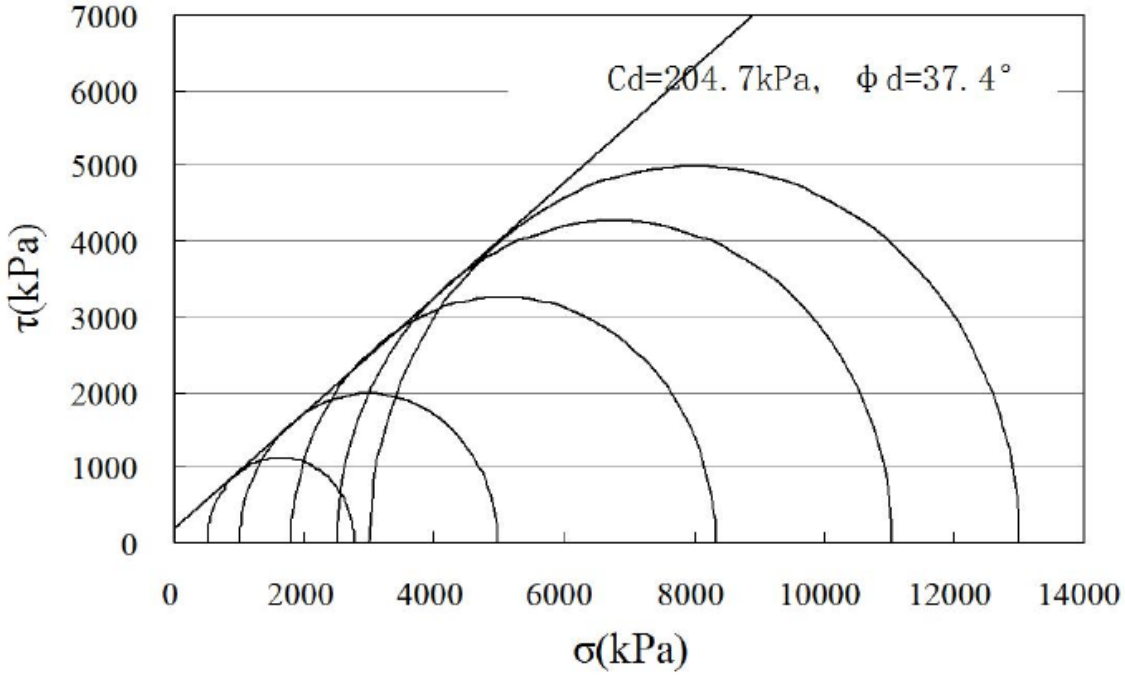


Figure 17– Triaxial test: Mohr-Coulomb circles for 3B – Saturated

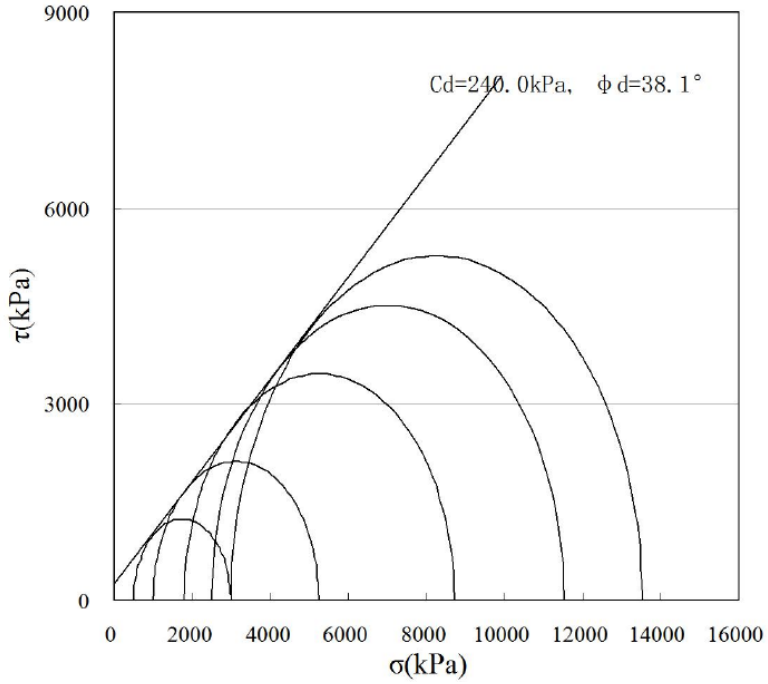


Figure 18– Triaxial test: Mohr-Coulomb circles for 3B – Dried

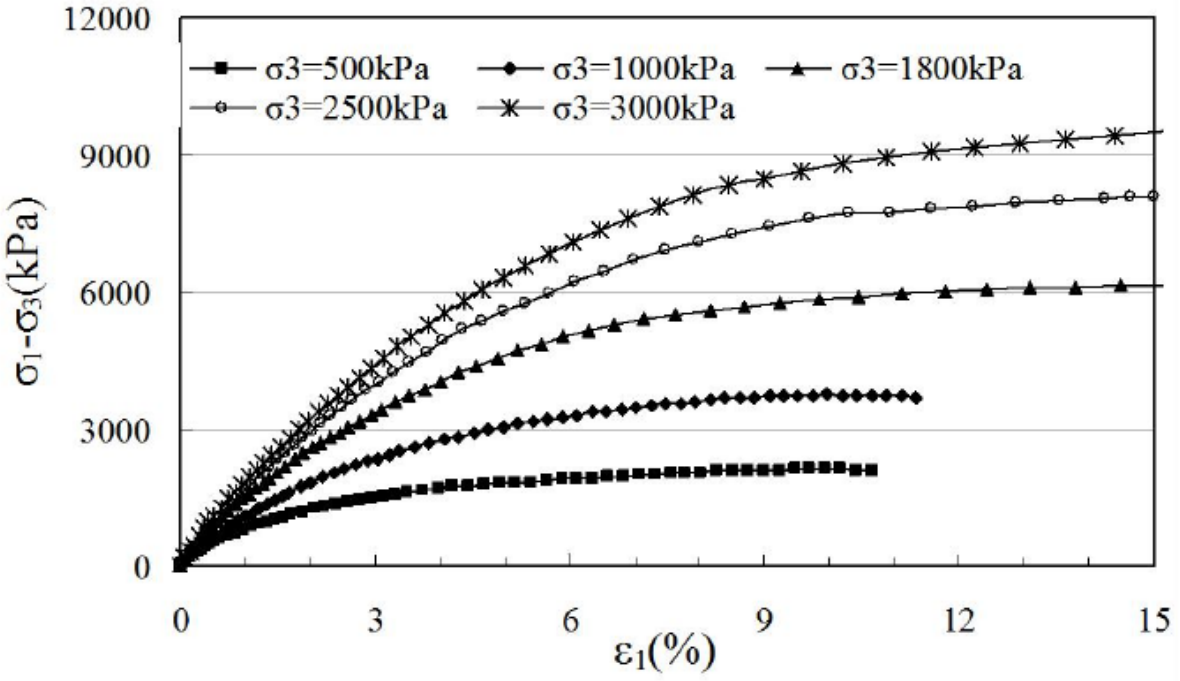


Figure 19 – Triaxial test: deviatoric stress (q) vs. axial strain (ε1) for 3C – Saturated

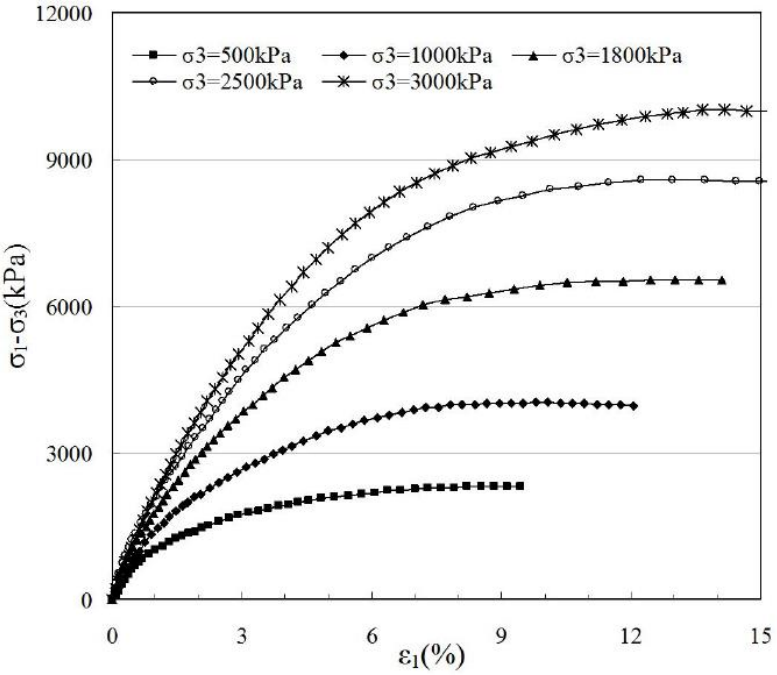


Figure 20– Triaxial test: deviatoric stress (q) vs. axial strain (*ε*1) for 3C – Dried

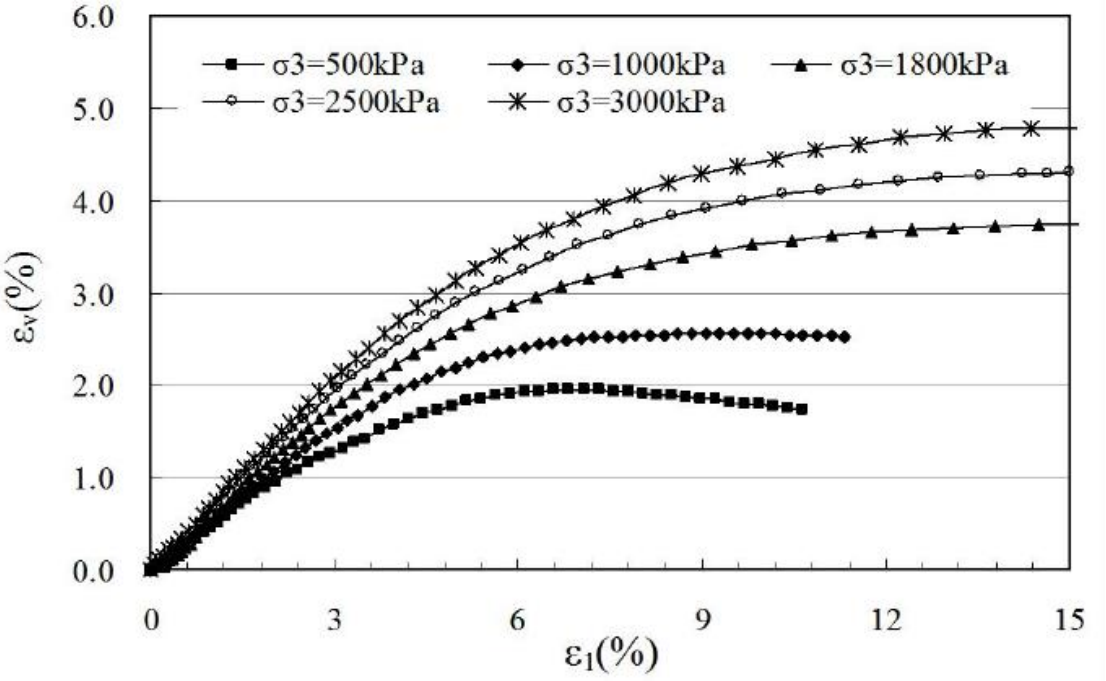


Figure 21 – Triaxial test: volumetric strain (*ε*v) vs. axial strain (*ε*1) for 3C – Saturated

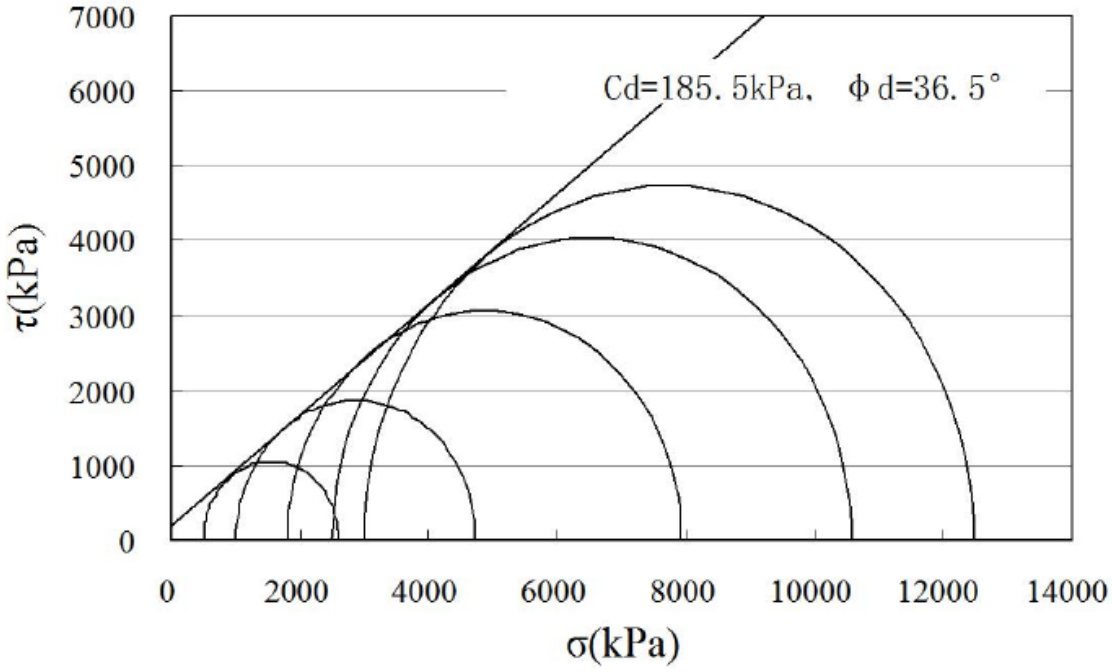


Figure 22– Triaxial test: Mohr-Coulomb circles for 3C – Saturated

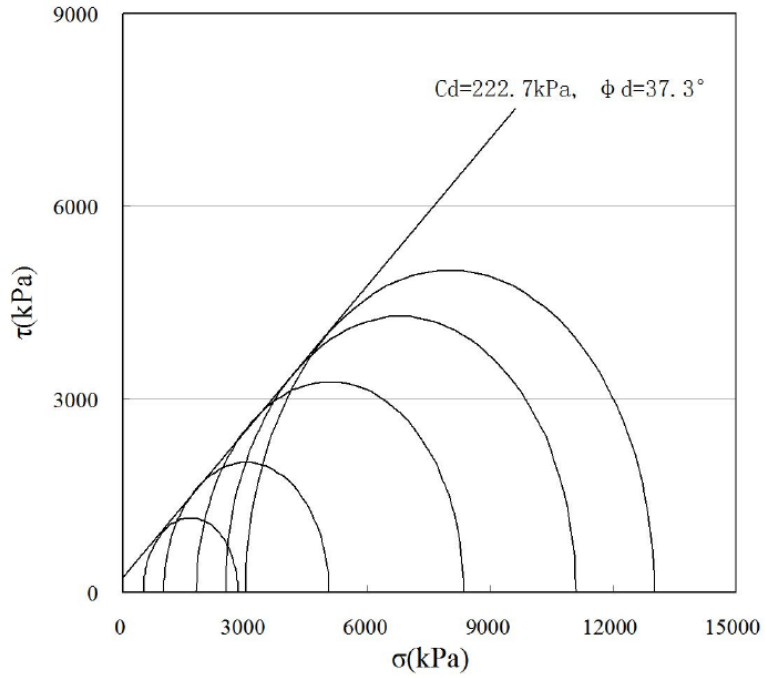


Figure 23– Triaxial test: Mohr-Coulomb circles for 3C – Dried

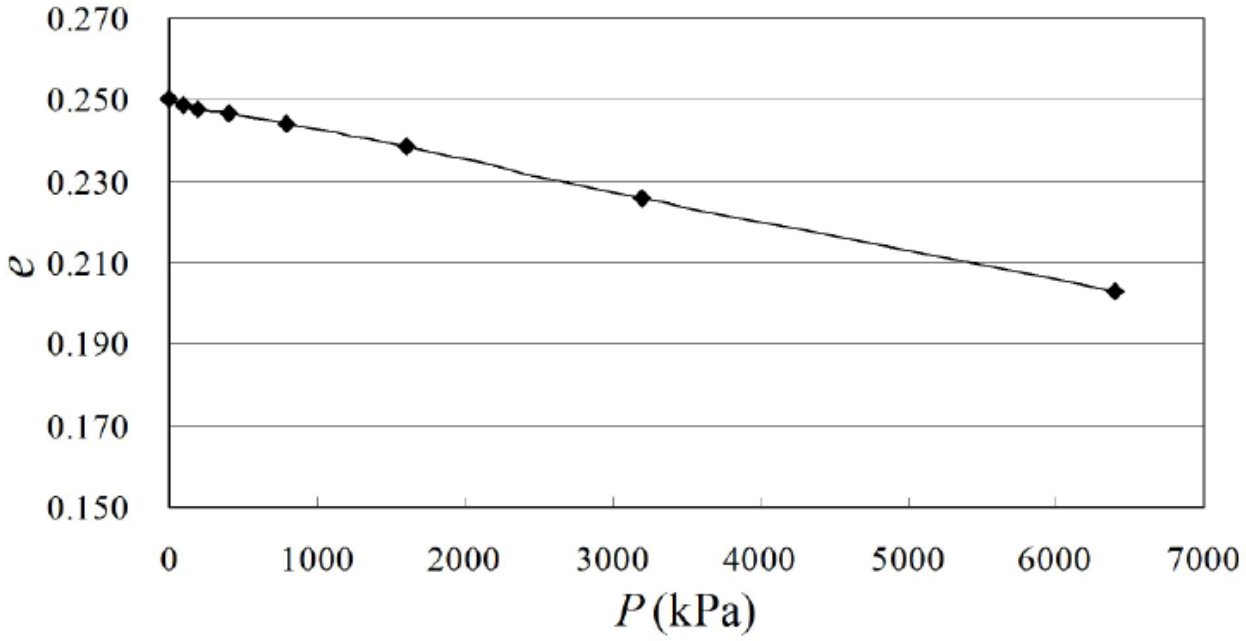


Figure 24– Oedometer test: Void ratio vs. axial pressure for 3B – Dried

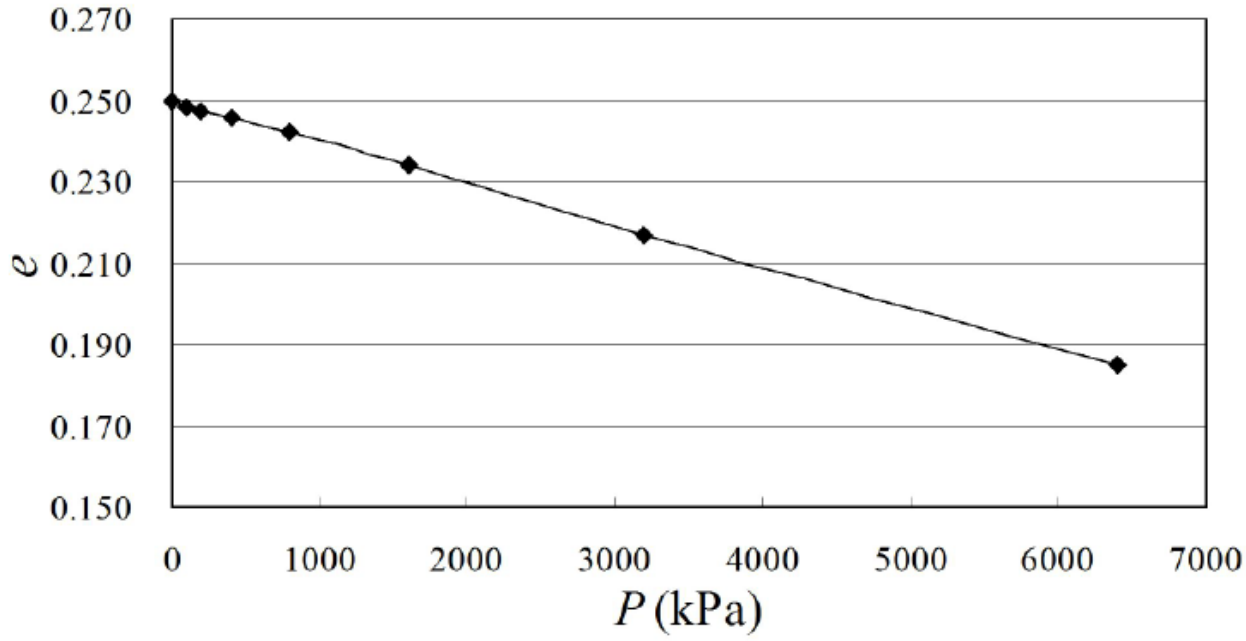


Figure 25– Oedometer test: Void ratio vs. axial pressure for 3B – Saturated

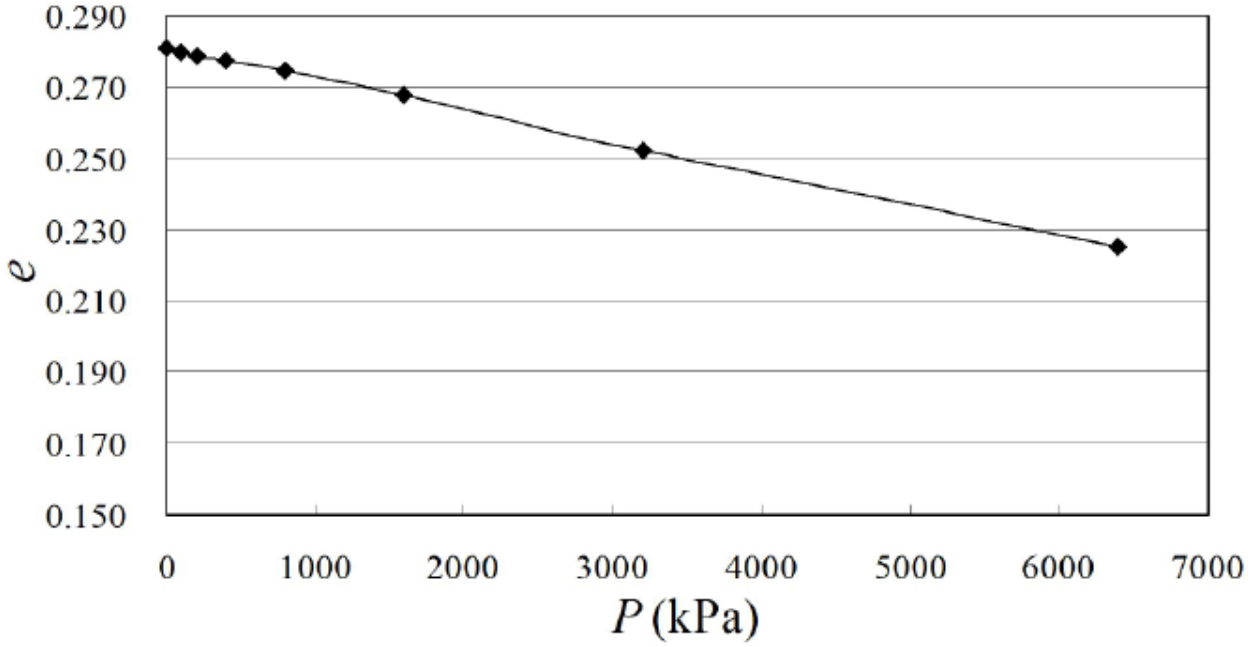


Figure 26– Oedometer test: Void ratio vs. axial pressure for 3C – Dried

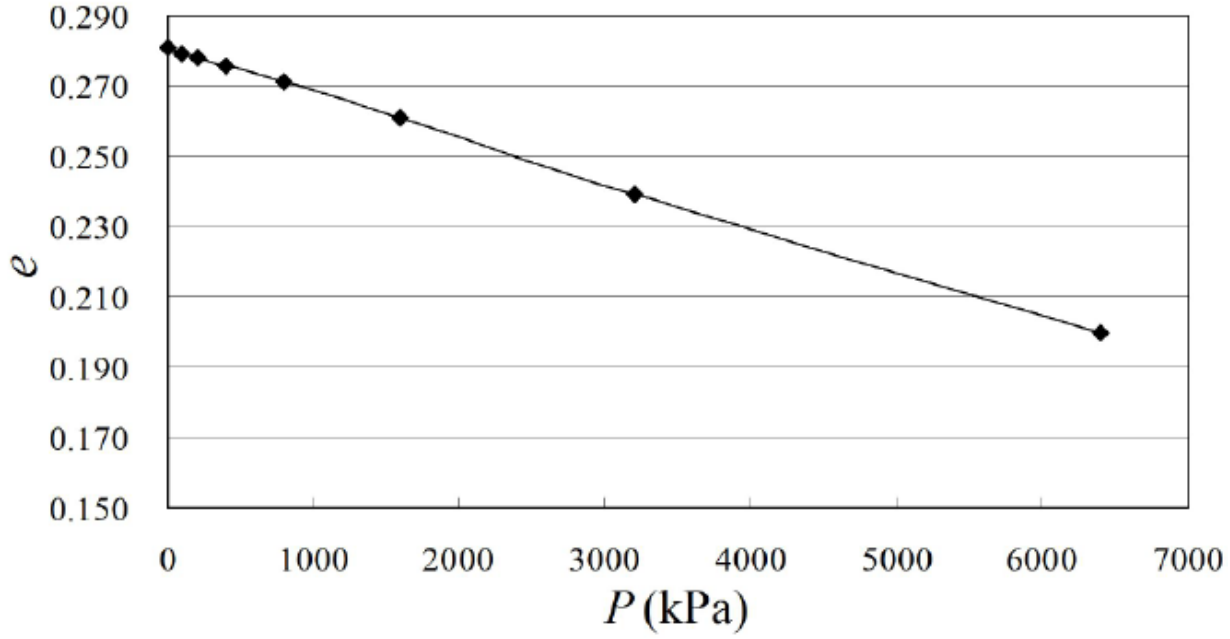


Figure 27– Oedometer test: Void ratio vs. axial pressure for 3C – Saturated

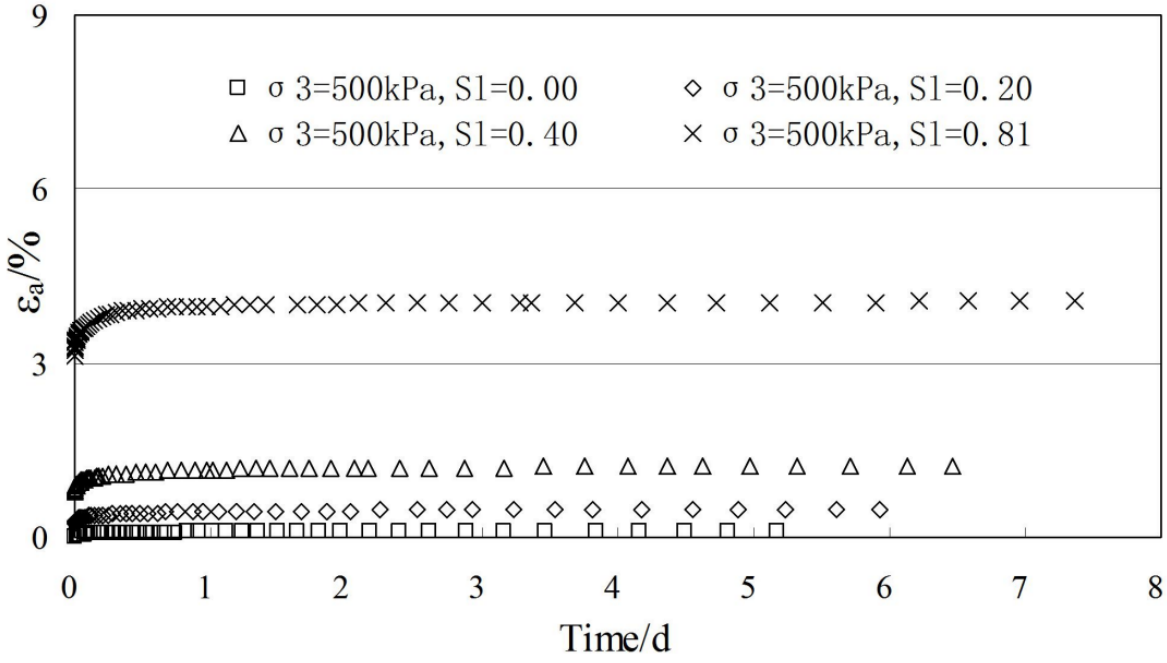


Figure 28 – Creep test curves of main rockfill zone material – ε_a vs. time - σ_3 = 500 kPa

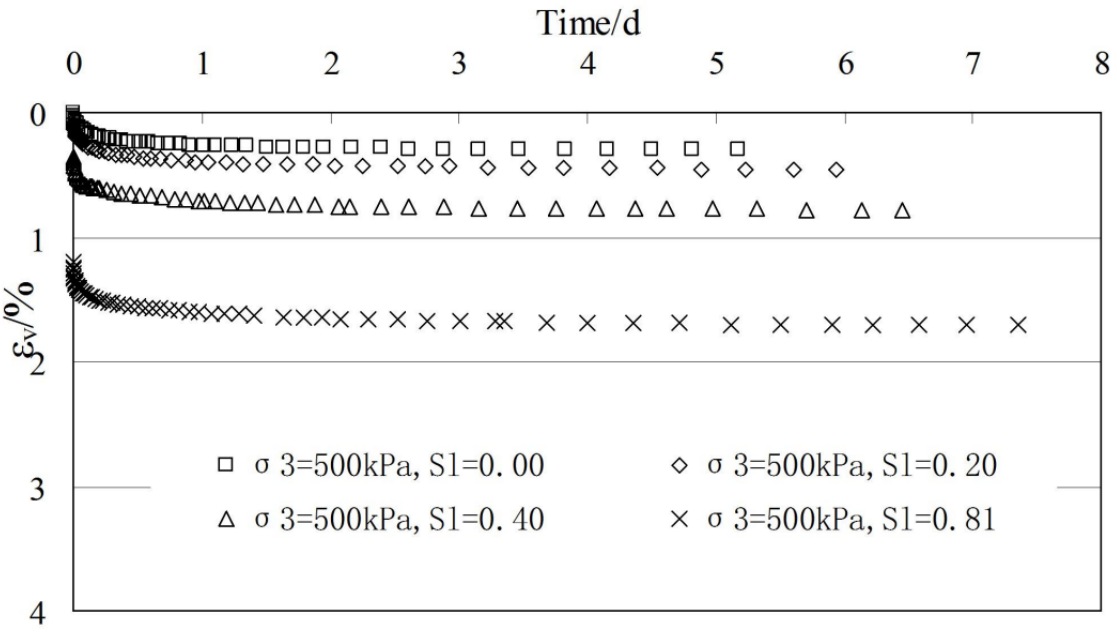


Figure 29 – Creep test curves of main rockfill zone material – ε_v vs. time - σ_3 = 500 kPa

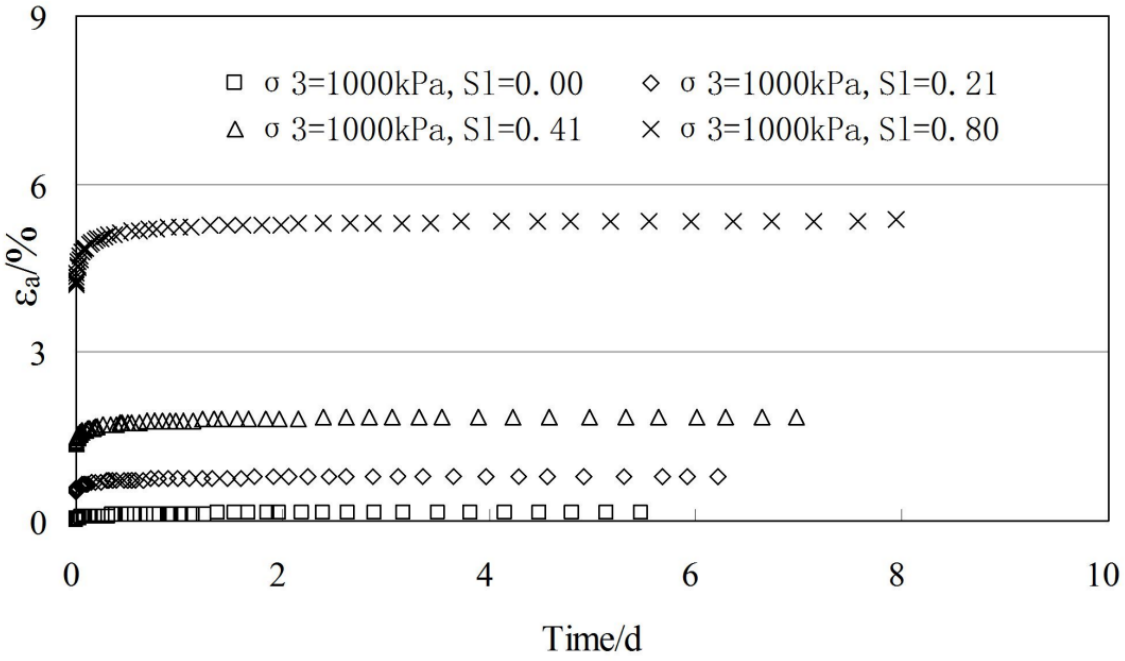


Figure 30 – Creep test curves of main rockfill zone material – ε_a vs. time - σ_3 = 1000 kPa

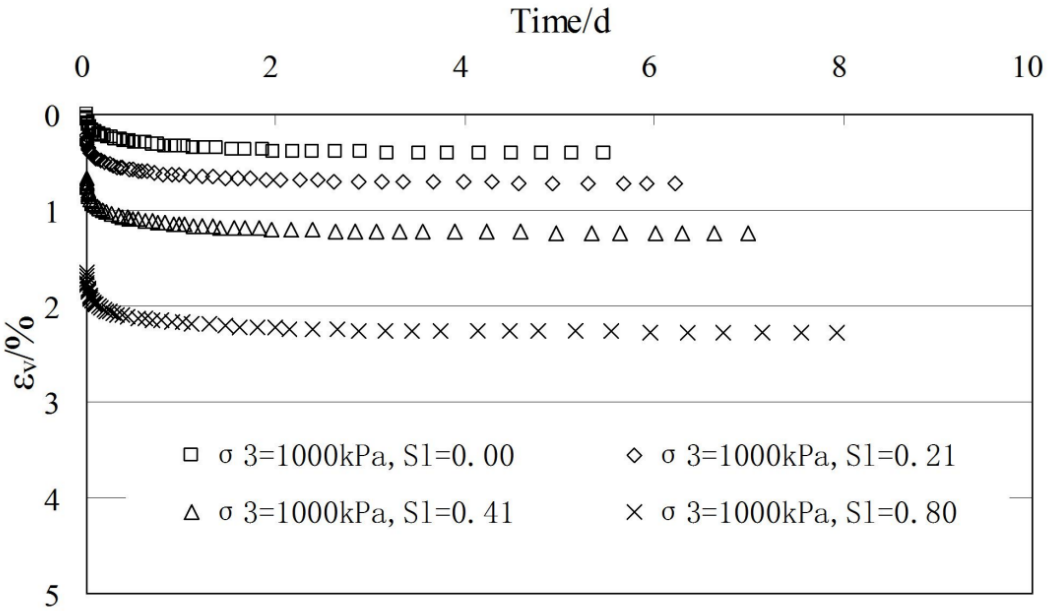


Figure 31 – Creep test curves of main rockfill zone material – ε_v vs. time - σ_3 = 1000 kPa

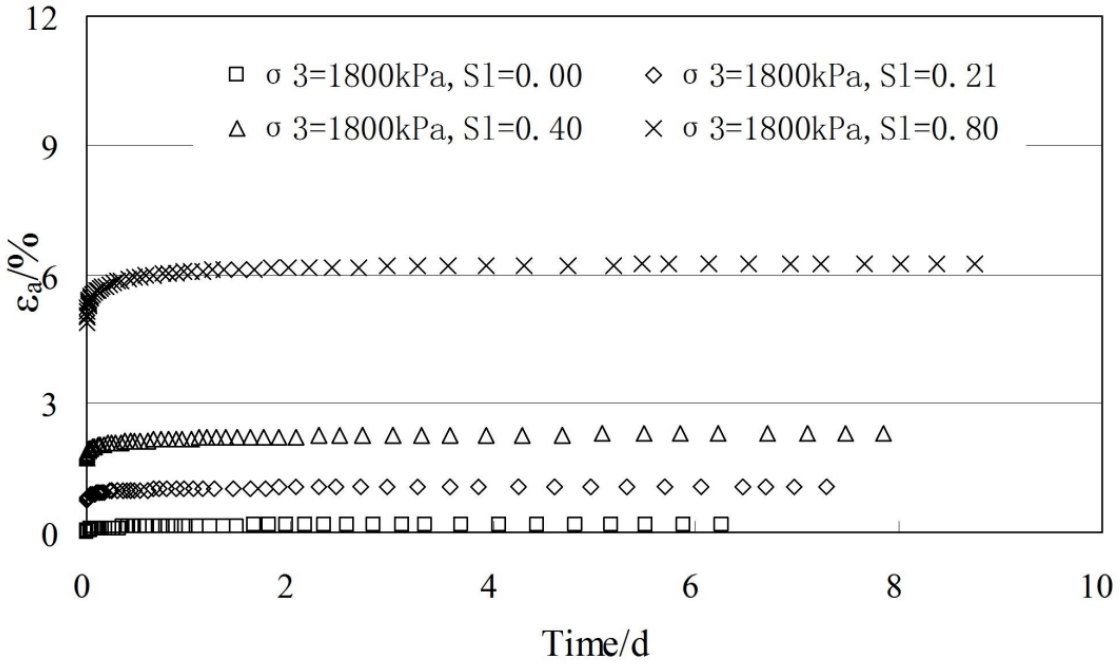


Figure 32 – Creep test curves of main rockfill zone material – ε_a vs. time - σ_3 = 1800 kPa

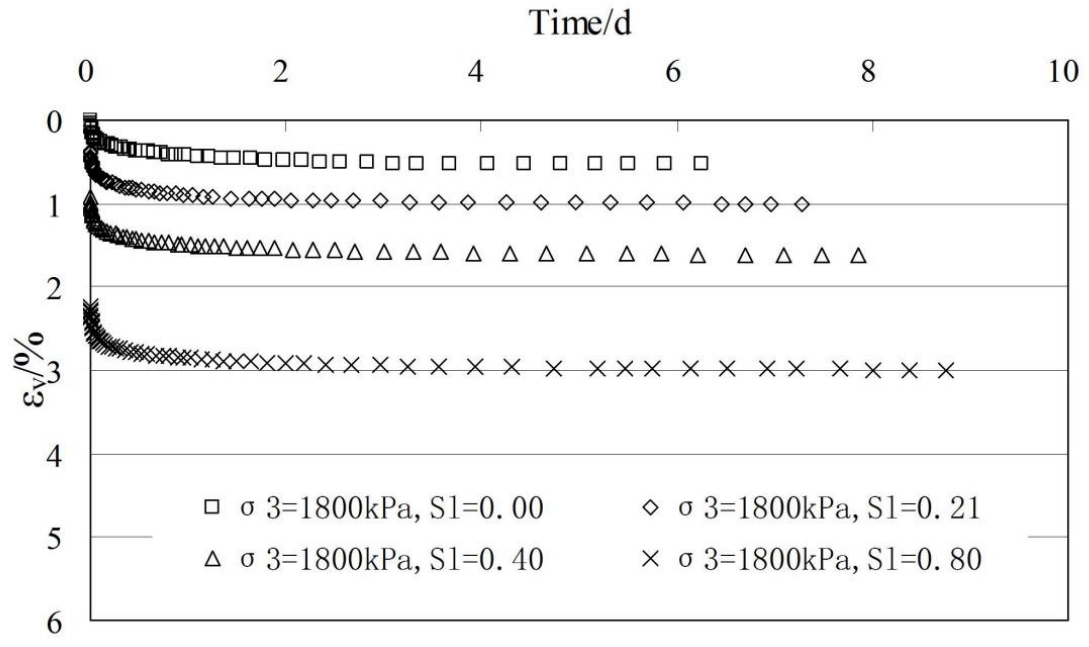


Figure 33 – Creep test curves of main rockfill zone material – ε_v vs. time - σ_3 = 1800 kPa

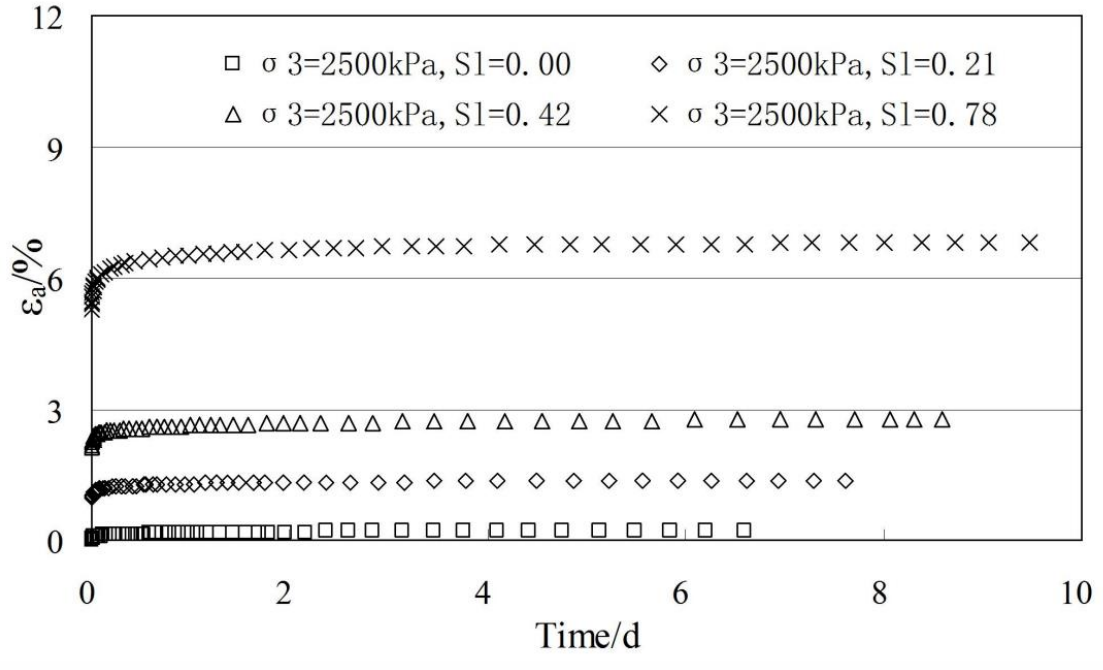


Figure 34 – Creep test curves of main rockfill zone material – ε_a vs. time - σ_3 = 2500 kPa

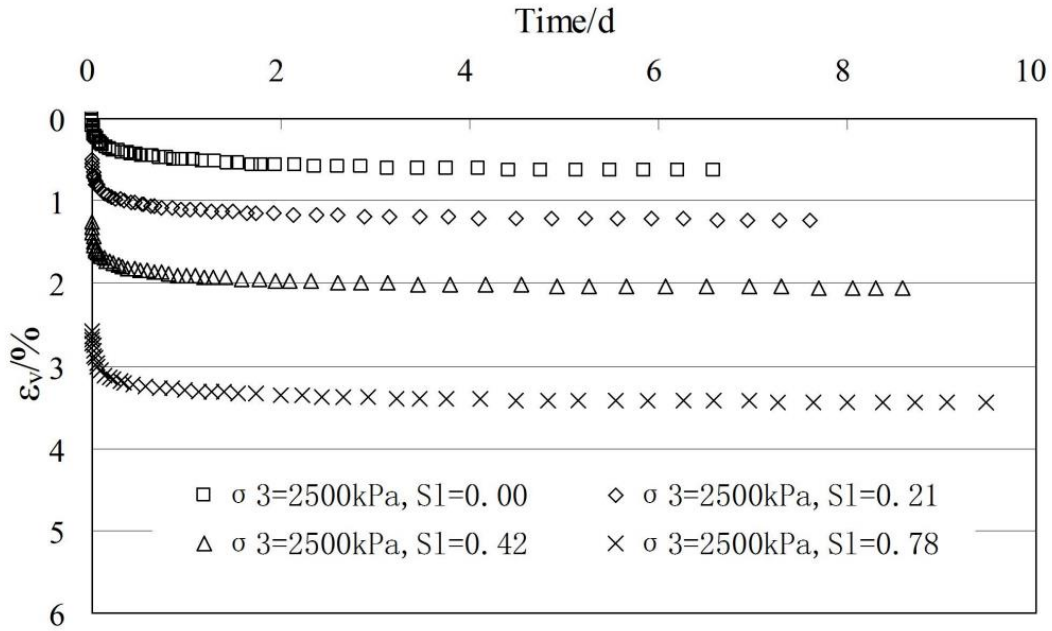


Figure 35 – Creep test curves of main rockfill zone material – ε_v vs. time - σ_3 = 2500 kPa

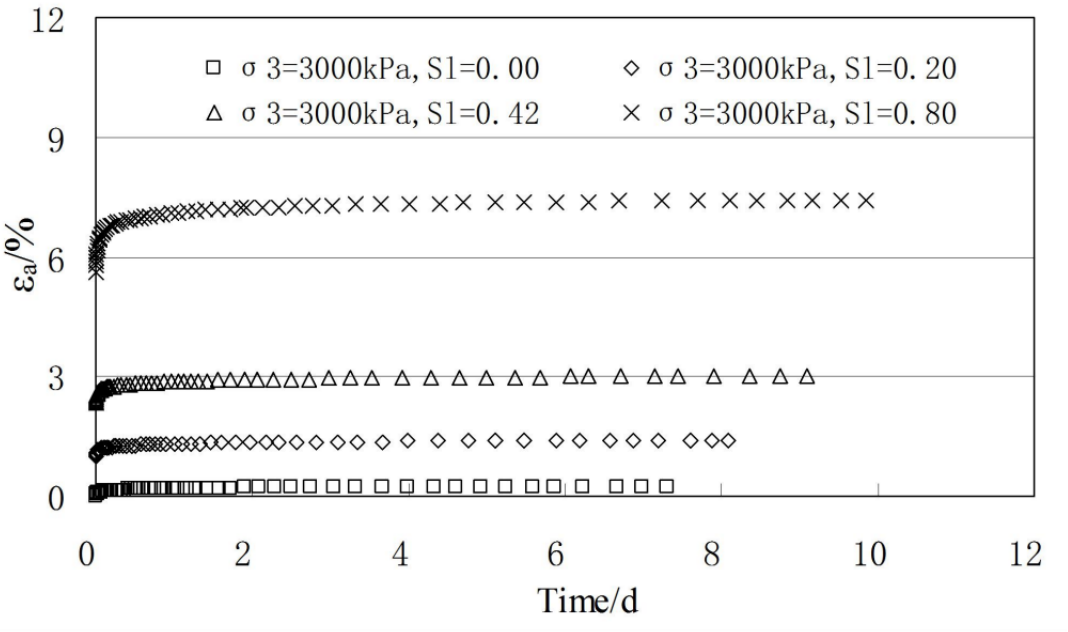


Figure 36 – Creep test curves of main rockfill zone material – ε_a vs. time - σ_3 = 3000 kPa

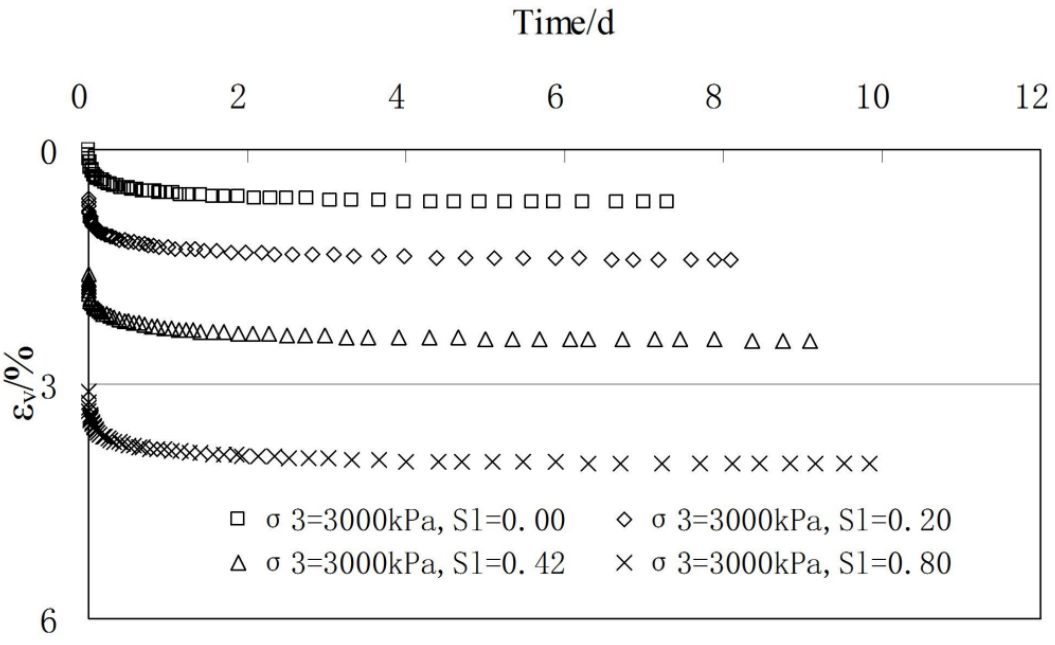


Figure 37 – Creep test curves of main rockfill zone material – ε_v vs. time - σ_3 = 3000 kPa

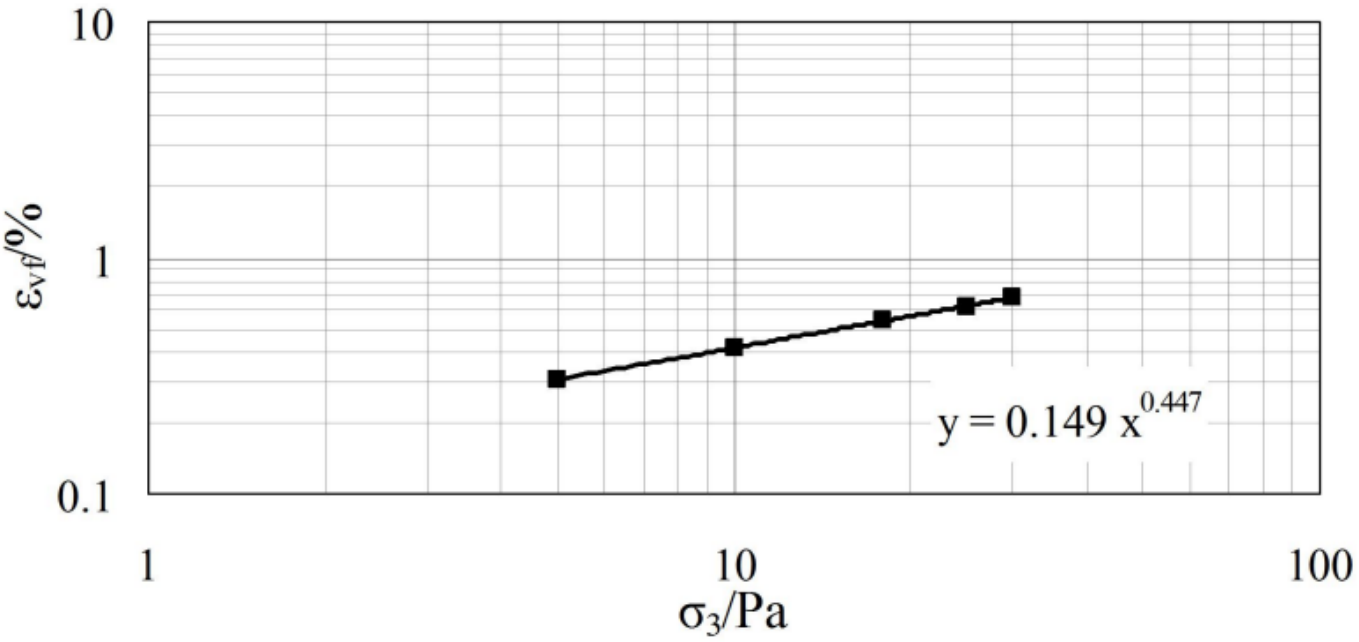


Figure 38– Triaxial creep test: ε_{vf} vs σ_3

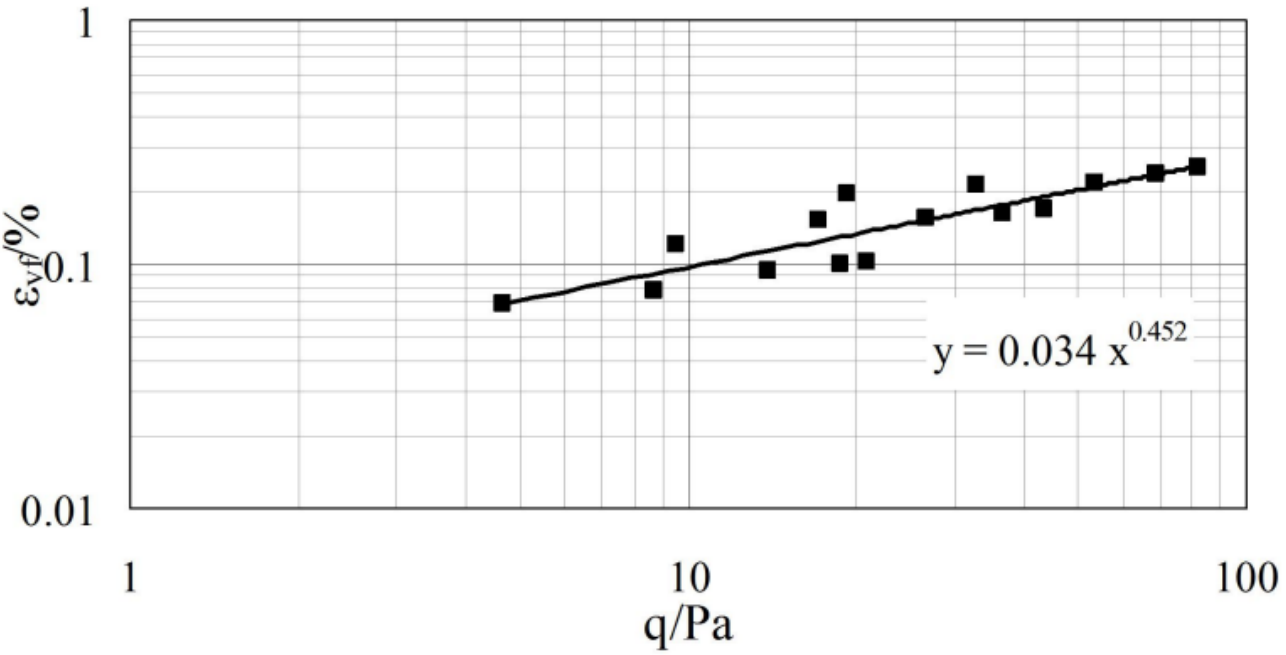


Figure 39– Triaxial creep test: ε_{vf} vs q

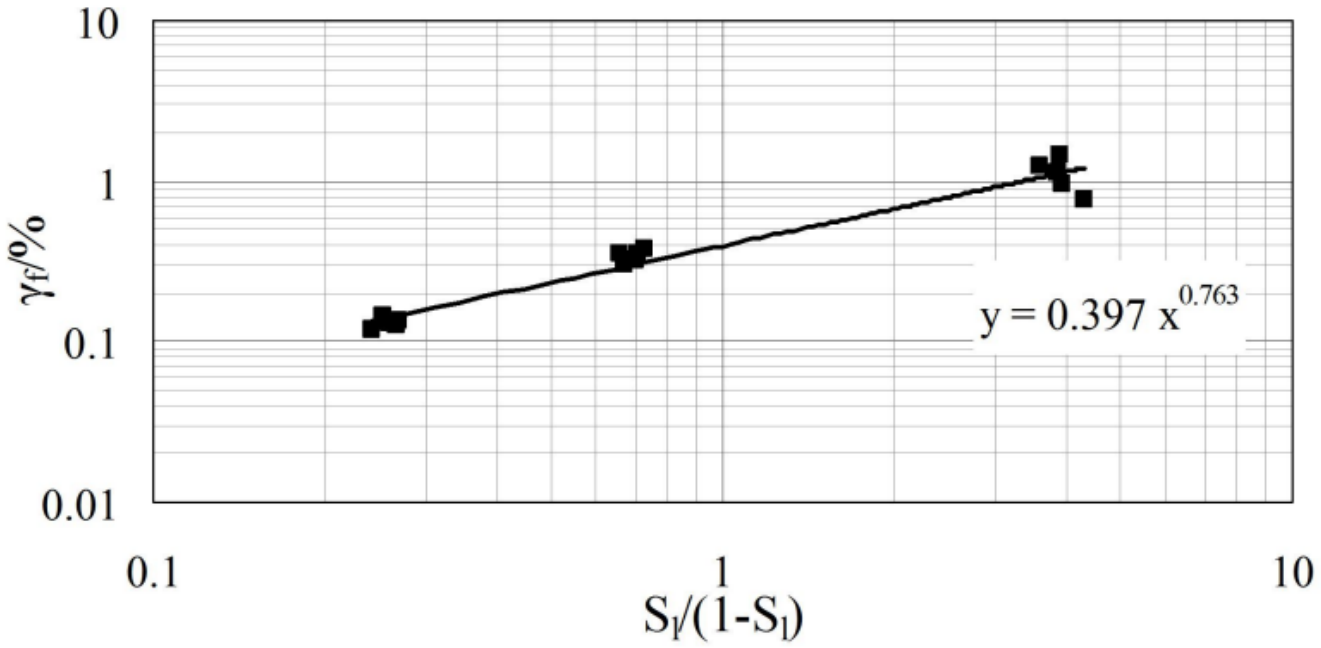


Figure 40 – Triaxial creep test: γ_f vs S_l

APPENDIX B

MONITORING DATA CORRECTIONS

Table 3– Corrections considered for the first settlement measures

Device	Installation elevation	Rockfill elevation at zero-reading	Gap (m)	Correction (cm)
TC11,2	563.59	566.5	2.91	2.2
TC9,2	601.50	609.6	8.10	12.4
TC7,2	636.70	661.5	24.80	55.4
TC5,2	672.12	680.7	8.58	25.3
TC3,2	702.24	719.5	17.26	61.2

Table 4 - Corrections considered for the first horizontal displacement measures

Device	Installation elevation	Fill elevation at zero-reading	Gap (m)	Correction (cm)
RD10,2-1	563.0	594.5	31.5	0.0
RD10,2-2	563.0	594.5	31.5	0.3
RD10,2-3	563.0	594.5	31.5	-0.6
RD10,2-4	563.0	594.5	31.5	-2.1
RD10,2-5	563.0	594.5	31.5	-0.4
RD10,2-6	563.0	594.5	31.5	-1.5
RD10,2-7	563.0	594.5	31.5	-2.0
RD10,2-8	563.0	594.5	31.5	-0.3
RD10,2-9	563.0	594.5	31.5	1.5
RD10,2-10	563.0	594.5	31.5	2.8
RD9,2-1	601.5	612.5	11.0	-0.4
RD9,2-2	601.5	612.5	11.0	-0.4
RD9,2-3	601.5	612.5	11.0	-0.2
RD9,2-4	601.5	612.5	11.0	-0.3
RD9,2-5	601.5	612.5	11.0	-0.4
RD9,2-6	601.5	612.5	11.0	-0.4
RD9,2-7	601.5	612.5	11.0	-0.3
RD9,2-8	601.5	612.5	11.0	-0.4
RD9,2-9	601.5	612.5	11.0	-0.4
RD7,2-1	636.5	660.4	23.9	-3.7
RD7,2-2	636.5	660.4	23.9	-2.9
RD7,2-3	636.3	660.4	24.2	-0.5
RD7,2-4	636.5	660.4	24.0	1.3
RD7,2-5	636.6	660.4	23.9	4.0

RD7,2-6	636.6	660.4	23.8	6.4
RD7,2-7	636.5	660.4	23.9	6.9
RD5,2-1	671.5	684.8	13.3	1.4
RD5,2-2	671.5	684.8	13.3	1.6
RD5,2-3	671.5	684.8	13.3	1.4
RD5,2-4	671.5	684.8	13.3	1.4
RD5,2-5	671.5	684.8	13.3	1.4
RD3,2-1	701.7	716.1	14.4	1.1
RD3,2-2	701.7	716.1	14.4	1.1
RD3,2-3	701.7	716.1	14.4	1.1