# THE CHALLENGES ASSOCIATED WITH LABORATORY SCALE PHYSICAL MODELLING OF HIGH-PLASTICITY SPOIL MATERIALS

## WYZWANIA ZWIĄZANE Z MODELOWANIEM FIZYCZNYM W SKALI LABORATORYJNEJ MATERIAŁÓW O WYSOKIEJ PLASTYCZNOŚCI ZE ZWAŁOWISK POGÓRNICZYCH

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*Characterisation of spoil (surface mine overburden) material is essential when investigating geotechnical issues associated with the spoil, e.g., for investigating the stability of pit lakes formed with spoil or spoil-structure interaction for any structures built on the spoil as part of sustainable developments. A significant proportion of spoils found across European countries are classified predominantly as silty clay with significant plasticity index and low permeability. In this paper, the difficulties associated with laboratory testing of highly plastic spoil materials obtained from different post-mining sites within Europe are discussed. The issues associated with small-scale laboratory testing of field spoil samples, development of an equivalent spoil for performing physical modelling tests, and the difficulties of centrifuge tests with spoil models are discussed in detail.*

***Keywords:*** *centrifuge, laboratory testing, physical modelling, spoil*

*Charakterystyka odpadów pogórniczych (nadkładu kopalni odkrywkowych) jest niezbędna przy badaniu zagadnień geotechnicznych związanych ze zwałowiskami, np. w celu zbadania stabilności pokopalnianych zbiorników wodnych utworzonych ze zwałowanych materiałów lub interakcji zwałowisko-konstrukcja budowlana dla wszelkich konstrukcji zbudowanych na zwałowisku w ramach zasady zrównoważonego rozwoju. Znaczna część materiału zwałowego występującego w krajach europejskich jest klasyfikowana głównie jako ił pylasty o znacznym wskaźniku plastyczności i niskiej przepuszczalności. W niniejszej pracy omówiono trudności związane z badaniami laboratoryjnymi wysoce plastycznych materiałów pogórniczych uzyskanych z różnych terenów pokopalnianych w Europie. Szczegółowo omówiono zagadnienia związane z badaniami laboratoryjnymi w małej skali próbek materiału pobranego w terenie, opracowaniem materiału równoważnego do przeprowadzenia modelowania fizycznego oraz trudności związane z badaniami w wirówce geotechnicznej modeli materiałów zwałowych.*

***Słowa kluczowe:*** *wirówka, badania laboratoryjne, modelowanie fizyczne, zwałowisko*

## Introduction

Thermal power plants have played a significant role in the provision of power generation within Europe and the United Kingdom. Lignite needed for electricity generation is obtained by mining. For economical reasons, surface mining is widely adopted to extract the lignite. The overburden soil (or spoil) is excavated first and dumped to a location near the mine site before mining the lignite. After completion of mining activities, most post exploitation open pit voids are turned into water reservoirs, mostly dedicated to recreational purposes. Locally available spoil is used as fill material or as the faces of pit lakes. Further, with the scarcity of land and as a measure towards sustainable development, many researchers recommended the effective utilisation of post mine sites, especially for renewable energy generation through installation of solar panels or wind turbines. To understand the short- and long-term behaviour of pit lakes, especially under varying hydrological and climatic conditions or to understand the spoil-structure interaction that occur when developing infrastructure on spoil heaps, the engineering behaviour of spoil should be investigated. Due to randomness in the dumping techniques, spoil is usually considered as highly heterogeneous and can contain a wide range of particles, ranging from rock fragments to very fine-grained soil particles. A small amount of organic matter has also been reported in spoils of different areas, such as Poland and Turkey (Masoudian et al. 2019, Zevgolis et al. 2021). Apart from heterogeneity, the presence of highly plastic fine-grained soils with very low permeability across many post-mining sites has posed serious challenges to geotechnical engineers. Conventional characterisation tests with these high-plasticity spoils are more challenging and require extended timescales due to their low permeability.

Geotechnical centrifuge modelling is known for its stress-strain similarity in model and full-scale (prototype) cases and has been found to be advantageous for understanding the seepage and consolidation characteristics of fine-grained soils. Thus, to understand any complex geotechnical issues associated with spoil (stability of pit lakes or spoil-structure interaction), it is desirable to perform centrifuge experiments, since 1g modelling cannot simulate the stress-strain similarity, and field tests are uneconomical or not possible to attain certain physical or loading conditions. This study discusses several challenges associated with the physical modelling of spoil materials.

(a) (b)

Fig. 1. Field sample cores collected from (a) ČSA open pit mine and (b) Slatinice Dump

Rys. 1. Rdzenie pobrane w kopalni odkrywkowej ČSA (a) i na zwałowisku Slatinice (b)

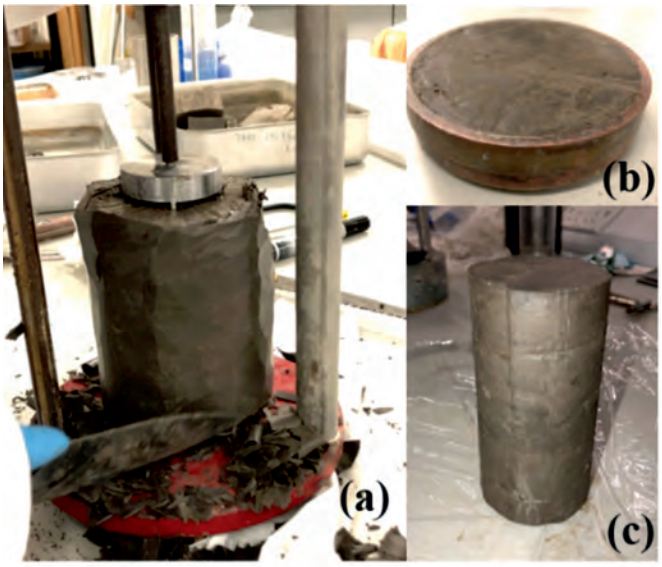

Fig. 2. (a) Sample trimming, (b) specimen for oedometer test and (c) specimen for triaxial test

Rys. 2. Przycinanie próbki (a), próbka do badania edometrycznego (b) i próbka do badania trójosiowego (c)

## Problem Statement

Extensive characterisation tests were conducted on core samples collected from the Czechoslovak Army Mine (ČSA) open pit mine, Czech Republic. This characterization was predominately done to evaluate the influence of material properties and geological features on short- and long-term stability of reservoir slopes and to investigate the feasibility of using reclaimed mine sites for onshore wind turbines. Further, for performing centrifuge experiments to study these specific applications, an equivalent spoil was needed that could exhibit similar engineering behaviour as the field spoil from the Czech Republic. This paper discusses several challenges faced while performing the laboratory characterisation tests, developing the equivalent spoil and finally, while performing centrifuge experiments using the equivalent spoil.

## Major challenges related to physical modelling of spoil

### *Characterizing the field spoil*

To simulate the spoil behaviour in the centrifuge, it is essential to first understand the behaviour of spoil in the field. For this, extensive in-situ and laboratory tests were performed on lignite mines located within European Union. Extensive cone penetration tests (CPTs_ were performed along Lake Most, Czech Republic, Slatinice Dump, Czech Republic and Jóźwin inner dump, Poland. Spoil sample cores were collected from the ČSA open pit mine and Slatinice Dump, Czech Republic. Figure 1 shows images of typical cores collected from the field.

Extensive soil characterisation tests were performed to evaluate the index (Atterberg limits, particle size distribution analyses, specific gravity tests) and engineering properties (oedometer tests, triaxial tests and simple shear tests) of the spoil samples received from the field. The samples extracted from Slatinice Dump possess particle sizes ranging from gravel to clay. Therefore, it was not possible to perform oedometer tests or standard triaxial tests on undisturbed samples extracted from the Slatinice Dump as the presence of gravel size particles demands a minimum sample size that exceeds typical oedometer and triaxial test equipment. Therefore, most of the testing was focused on cores extracted from the ČSA open pit mine. The samples received from the ČSA open pit mine were very stiff (semi-solid), especially those from deeper depths, with a unit weight of around 21 to 22 kN/m$^3$. Therefore, unconventional techniques had to be employed to trim the samples to the required diameter and length for triaxial and oedometer tests without disturbing the actual structure of the soil. Figure 2 shows one of the sample trimming techniques followed for extracting specimens for oedometer and triaxial testing.

Figure 3 shows the particle size distribution and Figure 4 shows the plasticity characteristics of the field spoil samples collected from the ČSA open pit mine. The results of field CPTs and other laboratory characterisation tests performed on spoil cores collected from the field was discussed in detail in Garala et al. (2022a and b). In summary, the laboratory characterisation of ČSA open pit mine field spoil indicates that the spoil is predominantly of silty clay with plasticity index ranging from 18% to 29% and possess very low permeability of 0.9 $\times 10^{-11}$ m/s. Because of this problematic fine-grained soil, even simple characterisation tests took considerable amounts of time. For example, for performing sieve analysis using a hydrometer, some specimens have almost 15% to 40% soil particles that did not settle after three days. For saturating oedometer specimens, samples had to be placed within a vacuum chamber with a certain stress applied on the upper surface top to avoid sample swelling during saturation. In triaxial tests, some specimens took more than a month to saturate. Thus, laboratory characterisation of spoil posed many challenges and significant experimental resources over long periods of time.

## Development of equivalent spoil

The engineering behaviour of spoil needs to be explored either to understand the stability of reservoir slopes under various geological and climatic conditions or for the effective utilisation of reclaimed mines for sustainable infrastructure (e.g., onshore wind turbines). For performing any centrifuge experiments with spoil, a large quantity of spoil is required. Further, in order to compare the results from different centrifuge experiments, the spoil behaviour should be consistent between experiments. It is not possible to obtain a large amount of spoil from the field or expect it to exhibit consistent behaviour between tests considering the wide heterogeneity exhibited by spoil in the field. Therefore, the development of an equivalent spoil was required that could exhibit similar characteristics as the characterised field spoil.

To develop an equivalent spoil that can exhibit similar characteristics as field spoil samples collected from different mine sites across Europe, different proportions of fine sand or silt and clayey soils were tested. Similarity in the particle size distribution and Atterberg limits (liquid limit, plastic limit and plasticity index) between field spoil and equivalent spoil was considered for the initial selection of equivalent spoil. In this process, different proportions of plastic sandy silt and kaolin were mixed to determine the Atterberg limits and consolidation characteristics, with results shown in Table 1. In Table 1, the sandy silt was obtained by sieving a silty sand obtained from Sheffield, UK, which was produced as a by-product of the washing process of quarry aggregate.

Though a good range of plasticity characteristics and consolidation characteristics were obtained from the combination of the silt from the Sheffield silty sand mixed with kaolin, it would have been overly laborious and time consuming to sieve the Sheffield silty sand to get the required amount of silt. Thus, it was decided not to use the sieved silty sand. Though sand and clay of different sizes and grade, respectively, are commercially available, plastic silt is not currently commercially available. After a thorough investigation, commercially available crushed quartz sand (A50 silica flour) in silt particle size range was found. However, as these silt particles are crushed sand, they don't exhibit any plasticity characteristics. Therefore, it was decided to use a portion of bentonite in the equivalent spoil to compensate for the non-plastic behaviour exhibited by the silt.

Table 2 lists the liquid limit and plastic limit values determined for different proportions of silt (A50 silica flour), kaolin and bentonite. After careful consideration, it was decided to adopt a 50% silt + 30% bentonite + 20% kaolin mixture as the equivalent spoil as this mixture exhibits a plasticity index close to that of the samples from the ČSA open pit mine spoil material. Figure 3 shows the particle size distribution of the proposed equivalent spoil in comparison to field spoil samples and Figure 4 shows the plasticity characteristics of field spoil and the proposed equivalent spoil. From Figures 3 and 4, the proposed equivalent spoil exhibits similar particle size distribution and plasticity characteristics as the field spoil. Based on oedometer tests, the field spoil had an average vertical permeability (k) of 0.9 $\times 10^{-11}$ m/s, whereas the proposed equivalent spoil has a permeability of 1.30 $\times 10^{-11}$ m/s, indicating good similarity of permeability characteristics between equivalent and field spoil. In terms of shear strength characteristics, based on consolidated isotropic undrained triaxial tests, the field spoil was found to have a very low critical state friction angle of around 20°, whereas the equivalent spoil had a critical state friction angle of about 28°. Considering the highly heterogeneous nature of field spoil, it may not be possible to match all geotechnical characteristics between the field spoil and the equivalent spoil. A more detailed comparison of engineering behaviour (consolidation, permeability and shear strength characteristics) of field spoil and the proposed equivalent spoil can be found in Garala et al. (2020b).

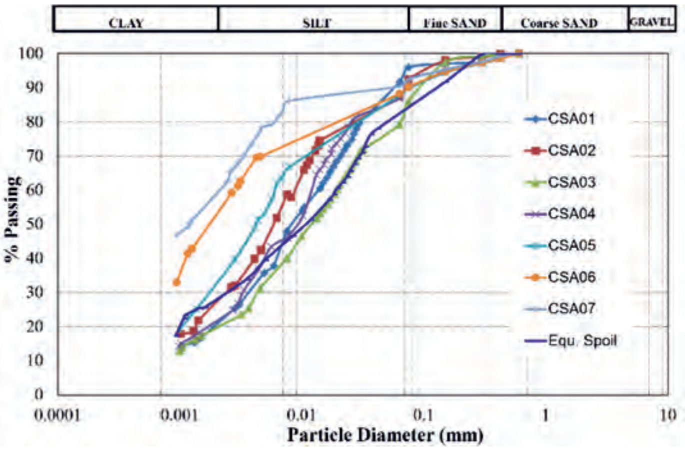

Fig. 3. Particle size distribution of field spoil and proposed equivalent spoil.
Rys. 3. Rozkład uziarnienia materiału pobranego w terenie i proponowanego materiału równoważnego.

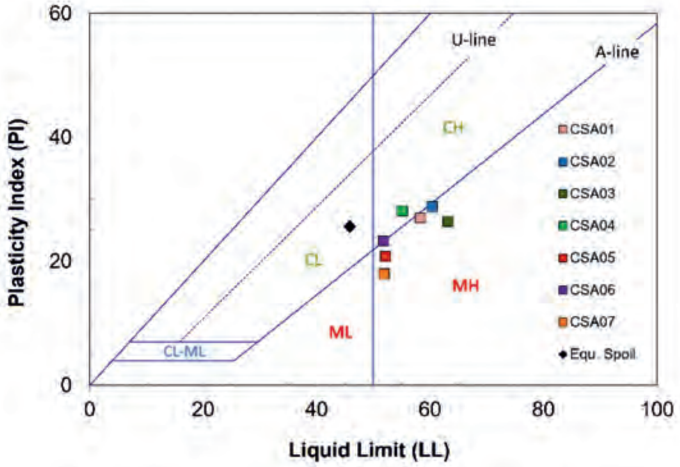

Fig. 4. Plasticity characteristics of field spoil and proposed equivalent spoil on plasticity chart.
Rys. 4. Charakterystyka plastyczności materiału pobranego w terenie i proponowanego materiału równoważnego na wykresie plastyczności.

### *Centrifuge models with equivalent spoil*

The compression index and recompression index of the proposed equivalent spoil were determined as 0.545 and 0.07, respectively, from oedometer tests. The average coefficient of consolidation ($c_v$) for the proposed equivalent spoil was determined as $5\times10^{-9}$ $m^2/s$ with a *k* of 1.30 $\times10^{-11}$ m/s. The spoil samples for oedometer tests were prepared by mixing dry equivalent spoil with water at a water content equivalent to twice the liquid limit of the equivalent spoil (~46%). Speswhite kaolin is widely used to simulate the behaviour of cohesive soils in centrifuge tests. Speswhite kaolin has a $c_v$ of $2.7\times10^{-7}$ $m^2/s$ and *k* of 3 $\times10^{-8}$ m/s, according to Springman (1989). The $c_v$ and of Speswhite kaolin are much larger than the equivalent

Tab. 1. Geotechnical characteristics of mixtures of sandy silt and kaolin clay.
Tab. 1. Charakterystyka geotechniczna mieszanek pyłu piaszczystego i gliny kaolinowej.

| Test Number | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Percentage | Sandy silt | 77 | 71 | 67 | 50 | 30 | 0 |
| | Kaolin clay | 23 | 29 | 33 | 50 | 70 | 100 |
| Plasticity index (%) | | 13.8 | 15.3 | 17.5 | 23.4 | 26 | 33.4 |
| Specific gravity, $G_s$ | | 2.60 | 2.64 | 2.61 | 2.60 | 2.60 | 2.60 |
| Compression index, $C_c$ | | 0.18 | 0.19 | 0.21 | 0.31 | 0.38 | 0.55 |
| Recompression index, $C_r$ | | 0.019 | 0.019 | 0.025 | 0.045 | 0.068 | 0.111 |
| Secondary compression index, $C_\alpha$ | | 0.0027 | 0.0028 | 0.0026 | 0.004 | 0.004 | 0.004 |

Tab.2. Geotechnical characteristics of mixtures of silt, kaolin and bentonite.
Tab. 2. Charakterystyka geotechniczna mieszanek pyłu, kaolinu i bentonite.

| Silt (%) | Kaolin (%) | Bentonite (%) | Liquid limit (%) | Plastic limit (%) |
|---|---|---|---|---|
| 60 | 40 | 0 | 32.5 | 18.2 |
| 50 | 40 | 10 | 34.7 | 17.6 |
| 50 | 30 | 20 | 40.2 | 18.5 |
| 50 | 20 | 30 | 45.9 | 20.2 |
| 60 | 0 | 40 | 60.0 | 26.1 |

spoil considered in this study. As a result, the time needed to consolidate the equivalent spoil for preparing centrifuge models was much longer than kaolin. For example, to 90% consolidate a soil thickness of 330 mm with double drainage, equivalent spoil will take up to 58.5 days, whereas kaolin needs just one day. Therefore, for soils like the equivalent spoil considered here, an alternative method of model preparation was warranted. Table 3 provides a brief summary of several centrifuge studies that dealt with cohesive soils, especially investigating slope stability. As shown in Table 3, compaction is a viable alternative to consolidation for preparing centrifuge models with fine-grained soils. However, it is difficult to obtain uniform compaction along the entirety of the centrifuge model; the lower layers might be over-compacted while compacting the upper layers if similar compaction energy is applied to all layers. In summary, preparing consolidated spoil models takes prohibitive timescales, but compacted samples may not be sufficiently uniform for centrifuge tests.

Further, the behaviour of consolidated and compacted soils will be different. For example, a significant difference in compacted and consolidated slope models highlighted by Hudacsek et al. (2009). Take and Bolton (2004) prepared a consolidated kaolin centrifuge model to investigate the effect of climatic conditions on the behaviour of a slope subjected to cycles of wetting and drying. The embankments were observed to swell and shrink significantly during each wet and dry season, with gradual downslope solifluction movements being generated. Take and Bolton (2004) suggested that progressive failure started to be generated after several years due to the gradual, incremental dilation of the over-consolidated kaolin towards critical state which will lead to collapse of the slope. Take and Bolton (2004) suggested that this was a possible general mode of failure for cohesive slopes under altering climatic conditions. On the other hand, Hudacsek et al. (2009) performed similar tests on a compacted kaolin clay model and found that no significant shrinkage and swelling movements were generated, but instead soil displacement trajectories were generally downslope. Furthermore, Hudacsek et al. (2009) reported that additional

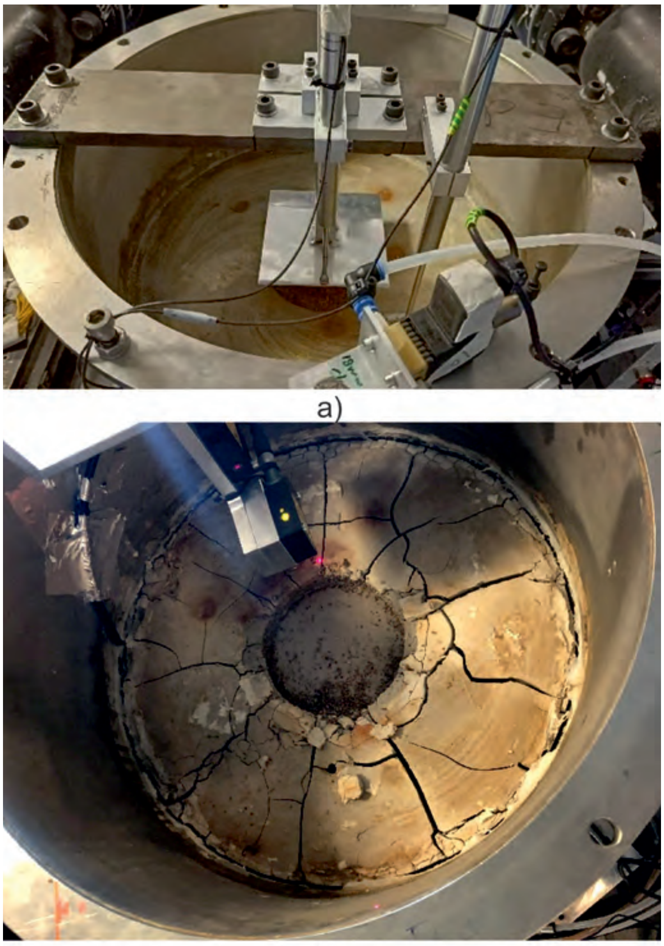
a)
b)

Fig. 5. Centrifuge model (a) Before the centrifuge test, and (b) After reconsolidation in the centrifuge
Rys. 5. Model wirówkowy (a) przed badaniem w wirówce oraz (b) po zagęszczeniu w wirówce

Tab. 3. A brief literature review of centrifuge models prepared by compaction technique
Tab. 3. Krótki przegląd literatury dotyczący modeli do wirówek geotechnicznych przygotowywanych techniką zagęszczania

| Study | Testing details | Model preparation technique |
|---|---|---|
| Zhang et al. (2011) | • 50g centrifuge tests<br>• Cohesive soil slopes<br>• $D_{50} = 0.03$ mm<br>• PL = 5%<br>• LL = 18%<br>• $\gamma_d = 1.5$ g/cc<br>• $k = 5\times10^{-5}$ cm/s<br>• $\phi' = 27°$, $c = 24$ kPa | • Soil was compacted by layers, 6 cm-thick for each layer, to the designated dry density in the model container. |
| Ling and Ling (2012) | • 100g centrifuge tests<br>• Sand-clay mixture<br>• Nevada sand and kaolinite with a fines content of 30%<br>• $D_{50} = 0.15$ mm (sand)<br>• PI = 24% (kaolinite)<br>• LL = 56% (kaolinite)<br>• $k = 1.8\times10^{-7}$ cm/s<br>• $\gamma_b = 2.2$ g/cc<br>• $\phi = 13°$, $c = 26$ kPa | • The inner part of slope was weathered slate rock, which was modelled using concrete with a rough surface.<br>• The cover soil was prepared by compacting the slope in 11 horizontal layers. |
| Ling et al. (2009) | • Tested till slope failure<br>• Sand and sand-clay mixtures<br>• Nevada sand and kaolinite with a fines content of 15% and 30%<br>• $D_{50} = 0.15$ mm (sand)<br>• PI = 24% (kaolinite)<br>• LL = 56% (kaolinite)<br>• $K_{sand}$+30%clay = $1.8\times10^{-7}$ cm/s | • A layer of soil foundation, 5 cm in thickness, was first prepared by compaction. The slope was then formed by compacting layers of soil, each of thickness 2.5 cm. |
| Zhang et al. (2012) | • 50g centrifuge tests<br>• Cohesive soil slopes with vertical and inclined cracks<br>• $D_{50} = 0.03$ mm<br>• PL = 15%<br>• LL = 28% | • The soil was compacted to 6 cm-thick layers in the model container using an impact hammer. |

hydraulic cycles provoked decreasing cyclic soil movement in the compacted fill, whereas Take and Bolton (2004) reported increasing displacement tending towards progressive failure in the intact over-consolidated kaolin. Thus, the fundamental behaviour of soil changes depending on whether it is prepared by consolidation or compaction.

Considering the pros and cons of available model preparation techniques, a new model preparation technique was developed in this study. First, the centrifuge model soil was prepared by compacting wet spoil at the required moisture content and density, followed by saturating the compacted model with deaired water. During the saturation process, the container was sealed at the top with a lid, and a gauge pressure of -90 kPa was applied at the top. The bottom of the container was connected to a deaired water supply and a slow rate of water ingress into the soil model was provided using a needle valve to avoid the formation of any preferential flow paths. Once the compacted model was saturated, the container was placed under a loading actuator and a static vertical stress equivalent to the preconsolidation stress of the compacted spoil (around 180 kPa) was applied. Once the model was consolidated under the applied stress, the stress gradually removed, and the model soil was ready for centrifuge testing. This proposed technique ensures that the whole soil model is subjected to the same vertical stress and minimizes the possibility of air pockets formed during the compaction process.

More details relevant to proposed model preparation technique and its validity discussed in Garala et al. (2020a).

### ***Testing spoil models within centrifuge***

Considering the very low permeability of spoil or equivalent spoil, centrifuge models take a very long time to reconsolidate within centrifuge conditions. The kaolin clay models can be reconsolidated within a few hours, whereas the equivalent spoil considered here needs several days to reconsolidate in the centrifuge. The time required to reconsolidate within the centrifuge is a function of model depth and ‘g’ level considered for the experiment. Running a centrifuge continuously for several days, especially unattended (late evenings to early mornings), requires considerable resources and incurs higher levels of risk than conventional tests where staff continuously monitor test conditions/parameters. The long-duration tests increase the likelihood of electronics and mechanical component distress/failure, which can lead can disruptions to data acquisition systems and/or require the test to be interrupted. Any small issue in centrifuge testing can result in a huge loss of time and resource. Therefore, careful preparation of models using reliable and robust equipment are essential and, while running the centrifuge experiments, regular data monitoring to check for possible issues and overall safety of tests are essential.

While reconsolidating the models in the centrifuge, the water level within the model was maintained constant with the help of a standpipe having continuous water supply. However, due to the low permeability of the spoil, it was found that the surface of the spoil still dried out (the evaporation rate was high due to strong winds within centrifuge environment). Figure 5 shows typical surface cracks that formed at the surface of centrifuge models after the test. These cracks propagate up to 10 to 30 mm from the surface. In order to avoid/reduce such cracks, the surface of the spoil was coated with several layers of transparent and flexible Plasti Dip®. For very long experiments, these coatings can at least minimize the formation of deeper cracks.

## Conclusions

Spoil materials from the Czech Republic were characterised using in-situ and laboratory tests to investigate their engineering behaviour. Based on results, an equivalent spoil was proposed that aligns well with the field spoil in terms of particle size distribution, plasticity characteristics and shear strength characteristics.

This paper discussed the difficulties associated with the characterisation of field spoil samples and the development of an equivalent spoil for centrifuge experiments. Further, this paper presented a new model preparation technique for centrifuge tests with high-plasticity, low-permeability soil/spoils. Finally, several issues associated with the centrifuge testing of these spoil materials were discussed and measures were suggested to mitigate the negative consequences of these issues.

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