Assessing the Suitability of Coarse Sand for the Sand flow Method in Immersed Tunnel Foundations

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Abstract: This research aims to investigate the feasibility of using coarse sand for the sand flow method in immersed tunnel foundations, with a specific focus on achieving the desired pancake diameter. The study was conducted in the context of the Khor al Zubair Immersed Tunnel project, Iraq, which faces light seismic activity. Traditionally, gravel beds are chosen as foundation for earthquake-prone areas, but the project opted for the innovative and cost-effective sand flow method using coarse sand with specific particle size requirements. The methodology involved conducting sieve analysis on Iraqi sand samples intended for sand flow foundation use. Based on the results, similar materials available in the Dutch market were examined and compared in terms of mineralogy and particle distribution. The relative density range was determined through laboratory tests, using Cone Penetration Test (CPT) values to derive the in situ relative density values. The test setup, comprising a water-filled basin and a modular enclosed plane simulating the tunnel element's underside was used to perform full scale pancakes. Measurements of hydraulic pressures, density, flow rates, and pressures during sand flow were recorded. Subsequently, CPTs were conducted after sand flowing and thereafter the plates were dismantled to make a point-cloud analysis measuring the pancake diameter. The results indicated that the desired relative density could not be achieved, irrespective of using coarse sand or the conventional fine sand typically employed for immersion tunnel foundations. However, the targeted pancake diameter was successfully attained. The conclusion suggests the need for further testing and the consideration of additional adhesives to potentially enhance the liquefaction resistance. Additional full-scale tests are recommended to investigate the feasibility of coarse sand in the sand flow method for immersed tunnel foundations. This research underscores the importance of advancing the sand flow method and exploring alternative materials for immersed tunnel construction in seismic zones.

Keywords: Sand flow; Immersed Tunnels; full-scale model; sand deposit foundation; liquefaction susceptibility.

1 Introduction

The installation of immersed tunnels has significant implications for the surrounding soil. Excavation and backfilling processes during tunnel construction alter the soil structure, leading to uncertainties and increased risks, particularly in earthquake-prone regions. The choice of foundation layer between the trench and tunnel bottom varies, with options including sand, gravel, or grouted foundations, often requiring additional support measures (Lunne et al., 1997; Lunniss & Baber, 2013).

The sand flow method, notably used in recent projects like the Marieholm tunnel in Sweden and the Maasdeltatunnel in the Netherlands, seeks to have each tunnel element supported by subsoil (sand) instead of temporary supports. Sand and water are pumped through embedded pipelines in the tunnel elements' floors. Outflow openings beneath the elements discharge the sand-water mixture, allowing it to settle and form a sand ring at ground level, resembling a "pancake." This process repeats until the sand ring reaches the tunnel element's bottom, generating "rivers of sand" at points of least resistance.

In the context of Iraq, traditional 0.2mm D50 sand, typically used for foundation via the sand flowing method, is unavailable. Therefore, testing the suitability of the chosen sand is crucial. A similar 0.55mm D50 sand used in the Zhoutouzui Tunnel project in China (Li et al., 2018) is being considered, as it proved non-liquefiable, given the relative density. A full-scale trial test will assess parameters such as pancake radius, uplift pressure, and sand flow rate, crucial for evaluating liquefaction stability. Liquefaction assessment can be accurately accomplished through the extrapolation of cone penetration test values (Lunne et al., 1997). Following the trial test, the sand gradation will be determined, and the addition of cement clinker will be considered if liquefaction is a concern.

In the design of Immersed Tunnel (IMT) structures, the arrangement of sand flow pipes has been influenced by cautious assumptions based on the Zhoutouzui tunnel test results conducted in China (Li et al., 2018). As a result, the design of the cast-in pipelines has been adjusted, expanding them from two rows to three. However, it is essential to acknowledge that a larger sand diameter can affect the

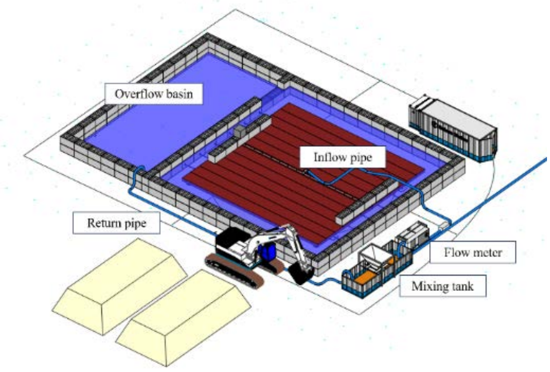

Figure 1 - Overview of test set-up

achievable pancake diameter, necessitating a thorough reassessment of these assumptions before proceeding with the sand flow process. This paper aims to provide a comprehensive evaluation of these critical considerations in the design and implementation of IMT structures.

2 Test model

2.1 Test set-up description

The test basin was constructed with dimensions measuring 19 m x 19 m x 1.6 m. It featured twelve watertight steel dragline mats, collectively representing the bottom of a tunnel element, and these mats were supported by two HEM-300 beams positioned atop six hydraulic jacks. The bottom of the steel dragline mats, replicating the tunnel element's base, was precisely set at the same height as specified in the Khor al Zubair Immersed Tunnel design, mirroring the 0.5m separation between the tunnel bottom and the trench top.
To counter uplift forces, sixteen concrete ballast blocks, each weighing 2.4 metric tons, were employed to stabilize the mats. In a separate mixing tank, the creation of a turbulent environment was achieved using jets to thoroughly mix sand and water before being pumped into the primary basin.

The testing encompassed a comprehensive examination of sand materials. Initially, a baseline test was conducted using Zeeuws sand, following the methodology established by Griffioen (Griffioen & van der Veen, 1972). Subsequently, four additional tests utilized Kaliwaal 41, a material chosen after conducting a comparison of the mineralogy and particle distribution of the available Dutch market materials to the Iraqi sand samples intended for sand flow foundation use. These tests aimed to assess material behaviour under varying flow speeds, both increased and reduced from the required flow speed, providing valuable insights into the material's response in different flow conditions.

Figure 1 provides an overview of the test configuration, while Figure 4 presents an image of the test setup after testing Kaliwaal material. For specific details on the arrangement of the hydraulic jacks, please refer to Figure 2.

Figure 4 - Test set-up after sand flowing Kaliwaal 41

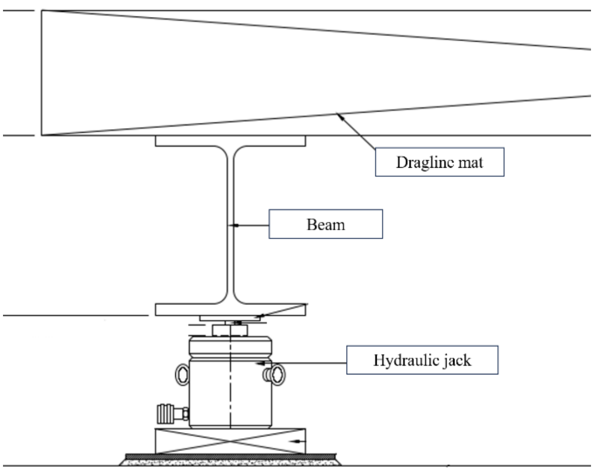

Figure 2 - Supports of the dragline mats

2.2 Test Materials

The susceptibility of sand deposits to liquefaction induced by seismic activity (Hashash et al., 2001) underscores the importance of maintaining the quality of sand within artificial sand deposit foundations. To minimize the risks associated with liquefaction, it is essential to utilize well-graded sand free from chemical admixtures and environmental contaminants, as emphasized in prior research (Guanghui et al., 2009). In accordance with the design principles established for the immersed tunnel project, the test sand has undergone rigorous screening to ensure its compliance. As illustrated in Figure 3, the particle size distribution of the sand aligns with the stipulated requirements for test materials, attesting to its suitability for use in the project. Table 1 shows the material characteristics of Zeeuws sand (Griffioen & van der Veen, 1972) and Kaliwaal 41.

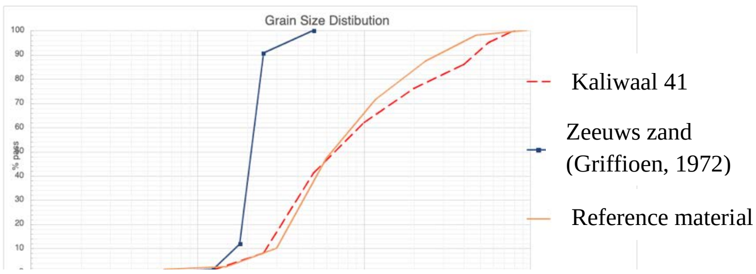

Figure 3 - Particle size distribution

Table 1 Material characteristics

	Zeeuws (baseline)	Kaliwaal 41
D_{50}	140 < D_{50} < 230 μm	700 μm
D_{60}/D_{10}	2,3 < D_{60}/D_{10} < 2,7	3,5
x < 63 μm	< 2%	< 2%

2.3 Test Parameters

A sequence of five sand flow tests was conducted, involving an initial baseline test employing Zeeuws sand. The primary purpose of this baseline test was to verify the functionality of the test setup by aligning its outcomes with the well-established methodology from Griffioen's research, thereby confirming the correct operation of the system.

Subsequently, the remaining tests utilized Kaliwaal 41 material, and they were designed to investigate the optimal process parameters, namely mixture speed and concentration. These parameters were varied to ascertain the most favourable combination. The specific input parameters used for each of the five tests are detailed in Table 2.

The analysed output parameters included:

- Uplift forces
- Pancake diameter
- Pancake build-up
- Sand segregation
- Relative density
- Test set-up operational parameters

For a comprehensive assessment, the measured uplift forces were compared with theoretically determined uplift forces, as outlined in the theory presented by Griffioen & Westersehelde (Griffioen & van der Veen, 1972).

Table 2 Input parameters

Test	Flow rate (m/s)	Average mixture density (kg/m^3)
1	4.4	n.a.
2	4.8	1131
3	4.7	1152
4	4.1	1129
5	5.6	1109

2.4 Measurement Methods

The methodology encompassed the comprehensive monitoring of several crucial parameters, allowing for a detailed examination of the test parameters:

1. **Uplift Forces**: Pressure transducers were employed to gauge the uplift forces generated by the sand pancake, which pressed against the cumulative effective weight of the dragline mats and concrete ballast blocks, effectively replicating the conditions beneath a tunnel element.
2. **Displaced Volume and Pancake Diameter**: LiDAR measurement was conducted after the test to determine the total displaced volume and pancake diameter, providing insights into the resulting formation.
3. **Conductivity (pancake build-up)**: In the methodology section, ground conductivity meters (GCM) were employed to capture changes in soil height within a 40cm vertical range at specific x, y coordinates. This methodology allowed for a comprehensive examination of the sand pancake's width and height variations during the test, even underneath the plateau. To optimize data collection, sensors were strategically placed in every other hole (see Figure *5*), with the remaining holes reserved for Cone Penetration Tests (CPTs) following the sand flow test. The precise operational steps for the GCM measurements are as follows:
   - **Data Averaging**: Data points were averaged over a 3-second time step to mitigate electrical noise.
   - **Time Standardization**: To synchronize measurements across all tests, t = 0 s was set as the reference point, considering variations in the start time of measurements.
   - **Detection of Sand Passage**: The moment of sand passage past a sensor was determined by a significant drop in the sensor's value, as the conductivity of water markedly differs from that of a sand-water mixture.
   - **Linear Analysis**: Employing linear interpolation and extrapolation, the sand height at specific time points was calculated.
   - **Data Visualization**: The acquired data points across the vertical and horizontal planes, along with time, were utilized to create a comprehensive 'pancake build-up graph.' This graph visually represents the evolution of the sand pancake over time, providing valuable insights into its development.
4. **Sand Segregation**: Visual inspection of bore holes was employed to assess sand segregation.
5. **Penetration Resistance and Relative Density**:
   Phase 1 involved a comprehensive assessment of several key parameters, including grain distribution (D50 calculation), maximum proctor density, optimal moisture content, saturation degree, and material settling form. These measurements provided a foundation for subsequent phases of the investigation.

   Phase 2 aimed to establish a calibration line that encompasses different relative densities and compaction conditions. Our goal was to closely replicate a calibration line from a prior study, which featured relative densities of 15, 50, and 70% (see Figure 6). This consistency with past research is crucial for maintaining accuracy.
   The calculation of relative density, a key factor in our study, relies on the penetration resistance data obtained through the Penetrologger Cone Penetration Test (CPT) (Tufenkjian et al., n.d.). These tests were conducted by penetrating the soil through the two rows of lifting holes in the steel dragline mats, with these holes temporarily covered during the sand flow process to ensure uniform test conditions.
   To determine the in-situ relative density (D_r) of the applied sand after the test, we relied on a combination of the well-established relations, such as those

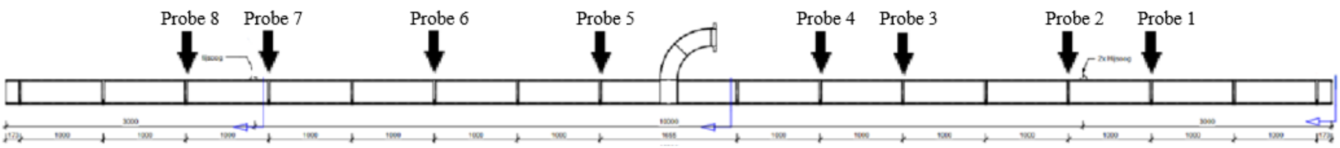

Figure 5 Location of conductivity probes

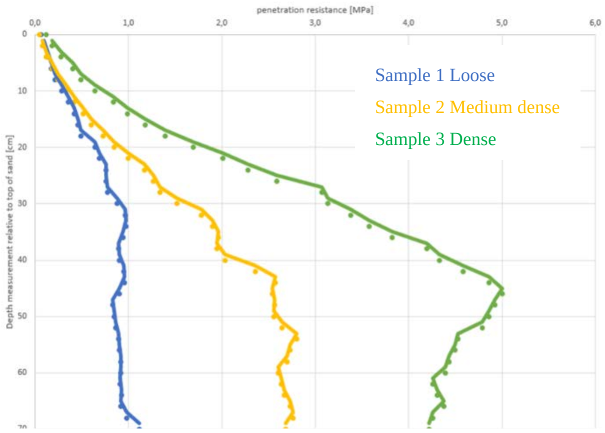

Figure 6 Cone penetration resistance from calibration test

formulated by Jamiolkowski (Jamiolkowski et al., 2003; Lunne et al., 1997) and results from phase 1.

The calculation of relative density is determined by considering the maximum and minimum pore content. The maximum pore content represents loose-poured sand, measuring 1660 kg/m³ at 0.0% moisture, while the minimum pore content reflects the maximum density attained through a weighted proctor test, with a density of 1824 kg/m³ at 10.3% moisture. This approach ensures the accuracy and reliability of our relative density calculations and offers a robust foundation for our study.

Furthermore, the methodologies that were used in order to assess the operational parameters that were tested during the study are explained as follows:

6. **Flow Velocities**: Inflow and outflow velocities to and from the mixing tank were consistently monitored to assess the fluid dynamics.
7. **Pipeline Pressure**: Pressure levels within the pipelines connecting to the mixing tank were under continuous scrutiny to maintain stable operational conditions.
8. **Mixture Concentration**: Regular recording of the density of the sand/water mixture was performed to gain insights into the mixture's composition and consistency throughout the experiment.

3 Results

The results section presents key findings related to uplift forces, pancake diameter, build-up, sand segregation, relative density, and test set-up parameters. These results provide insights into the performance and behaviour of sand flow foundations in immersed tunnel construction. They form the basis for our analysis and contribute to the field's advancement.

3.1 Uplift forces

The uplift forces were measured during, immediately after and 24 hours after the test. No reduction of uplift forces was measured after 24 hours, which can be explained by the coarse character of the sand material.

The difference of the uplift force before and after the test is presented in Table 3. During test 3, a local breakthrough of the dragline mats explains the large reduction in uplift forces.

The theoretically determined uplift forces (Griffioen & van der Veen, 1972) are also shown in Table 3. It can be concluded that the results were in the same order of magnitude as the uplift forces measured during the tests, but come out lower than measured. The uplift force is highly dependent on mixture density and production speed. The difference between the measured value and the theoretical value could be due to measurement errors in the mixture density. Verification of the theory is not accomplished in this test.

Table 3 Test results

Test	Uplift force from pancake - neasured (metric tons)	Uplift force from pancake - theoretical (metric tons)	Average diameter (m)
1	15	n.a.	11
2	47	22	15.2
3	33	24	12.7
4	50	21	13.6
5	50	19	16.7

3.2 Pancake diameter

The prescribed radius for the Khor al Zubair Immersed Tunnel, set at 7.3 meters (see Figure 7), was successfully attained in two out of the four conducted tests, see Table 3. This achievement suggests an observable correlation between the flow rate and the resultant pancake diameter. Collectively, the test outcomes unequivocally demonstrate the feasibility of achieving the stipulated radius requirement for the immersed tunnel project.

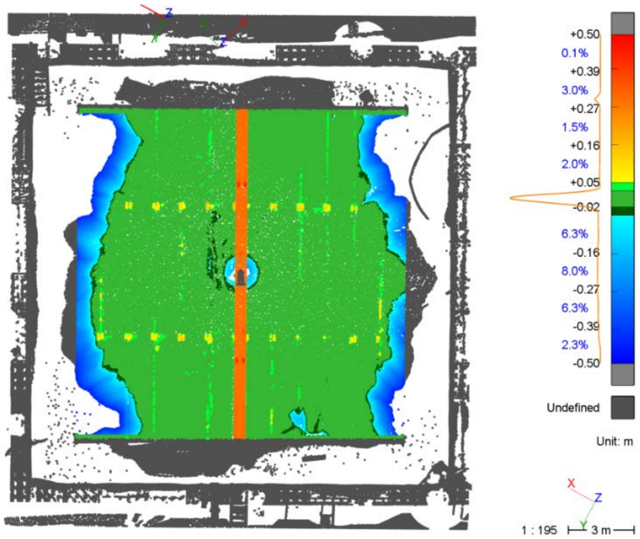

Figure 7 Sandflow test, 4th pancake with Kaliwaal 41

3.3 Pancake development

The accumulation of sand pancakes was quantified by measuring their diameter across predefined locations marked by conductivity probes, as depicted in Figure *12*. This approach facilitated real-time observations of the pancake formation throughout the duration of the test. Notably, the observed pancake evolution revealed distinct phases. Within the initial 10 to 20 minutes of sand flow initiation, the pancake exhibited a characteristic formation of a central crater. Subsequently, over a span of 40 to 50 minutes from the onset of sand flow, the central crater gradually closed, likely attributed to the consolidation of material around the previously formed ring structure at its periphery. Only after approximately 80 minutes, marking the latter stages of pancake production, did the material completely fill the void beneath the steel dragline mats. Figure 12 illustrates the data generated through the GCM measurements, providing a visual representation of these observations.

3.4 Sand segregation

Refer to Figure 10 for a representative depiction of a trial pit. The examination of both the trial pit and the soil samples extracted from each sand pancake reveals a consistent pattern of material segregation that is evenly distributed throughout the pancake's depth. However, it is noteworthy that within the uppermost 5-10 centimetres of the sand pancakes, a prevalence of coarser particles is evident. This phenomenon can be attributed to the washing out of finer particles when the gap between the pancake and the tunnel element narrows, leading to an increase in flow velocities. Consequently, these finer particles tend to accumulate in the outer edges of the pancakes, thus contributing to the observed coarser composition in the upper layers.

Figure 11 Small trial pit showing homogeneous sand build-up with a coarse top layer.

3.5 CPT and relative density

The results of the Cone Penetration Test (CPT) conducted during the initial test utilizing Kaliwaal 41 are graphically presented in Figure *11*, with similar outcomes observed in subsequent tests. Figure *11* exhibits a spectrum of coloured lines representing data obtained from various CPT locations distributed across the pancake's surface, as indicated by numbered CPT locations in Figure 5. Notably, the black line signifies the aggregated value of multiple CPT measurements, serving as a comprehensive indicator of the CPT values for this specific pancake. To examine these results, a comparative analysis was performed against the calibration test results depicted in Figure 6. This analysis reveals that the cone resistances consistently exhibit low values, notably falling below the threshold of 15% as indicated by the blue curve labelled 'loose' in Figure 6. Consequently, it can be deduced that the observed cone resistances in this study are generally characterized by a "loose" nature.

Figure 10 Result of Sand flow test with Kaliwaal 41

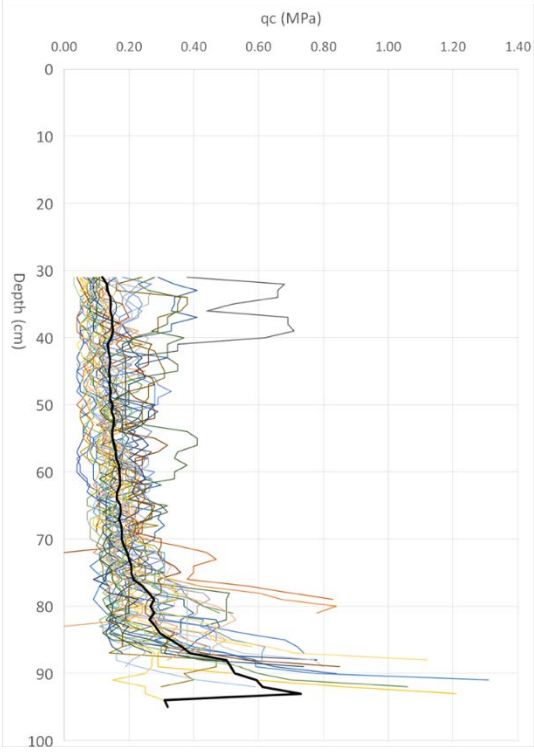

Figure 9 Cone penetration resistance made in the pancake after sand flowing

4 Discussion

1. Our study reveals the feasibility of creating 7.3-meter-radius sand pancakes using materials akin to Kaliwaal 41. This discovery hints at the potential use of materials falling within the range from Zeeuws sand to Kaliwaal 41 in sand flowing processes for immersed tunnels. This exciting

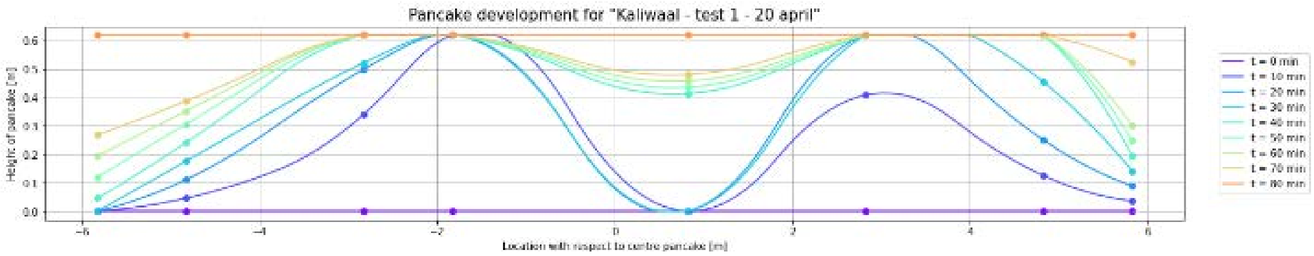

Figure 12 Pancake development using GCM sensors for Kaliwaal 41

prospect warrants further exploration and experimentation to assess the applicability of a broader spectrum of materials with intermediate properties. Future research could unveil the adaptability of sand flow techniques, accommodating diverse geological conditions.

2. Our research underscores the value of utilizing data gathered during the sand pancake formation, as measured by the Ground Concentration Measurement (GCM), for validating computational tools like TUDFlow3d. TUDFlow3d, a fully three-dimensional CFD solver, designed for simulating turbulent flow on an engineering scale, stands to gain significant insights from empirical data derived from real-world sand flow operations. This fusion of experimental results and computational modelling holds tremendous promise for enhancing our grasp of sand flow processes, offering the potential for more precise and efficient engineering solutions in the realm of immersed tunnel construction. Collaborative research in this area may pave the way for an enhanced integration of computational fluid dynamics in practical sand flow applications.

3. The determination of relative density through CPT values, as prescribed by (Lunne et al., 1997), has yielded consistently low values. These values are intrinsically linked to a percentage that serves as a basis for assessing material liquefaction susceptibility. Our study has raised concerns about the accuracy of CPT values in representing reality accurately. This prompts the need for exploring alternative methods to determine relative density from CPT data. Furthermore, the determination of relative density in our calibration tests may require further scrutiny to ensure the validity of the obtained values.

Ensuring a robust calibration necessitates a direct correlation between dry densities and relative densities. The established dry densities for different relative densities, such as saturated (Dr = 0%) at 1660 kg/m³, loose (Dr = 15%) at 1685 kg/m³, medium dense (Dr = 50%) at 1742 kg/m³, dense (Dr = 70%) at 1775 kg/m³, and optimal (Dr = 100%) at 1824 kg/m³, serve as a vital foundation for consistency with prior research and offer a valuable benchmark for future investigations and analysis.

4. Given the indications of liquefaction potential in the applied sand material based on our test results, it is prudent to consider and investigate the incorporation of cement clinker. A forthcoming test will be conducted wherein clinker material will be introduced to Kaliwaal 41. This research avenue holds the promise of shedding light on potential stabilization methods to mitigate liquefaction risks in sand flow applications.

4 Conclusions

In conclusion, the full-scale sand flow test conducted at the Ballast Nedam premises in Maarssen, Netherlands, provided valuable insights into the feasibility of using an increased grain size for sand flow applications. Several key findings emerged from this study:

1. **Uplift forces:** Uplift forces were examined during and after the tests. No significant post-test reduction was observed, likely due to the sand's coarse nature. Test 3 experienced a notable reduction, attributed to a dragline mat breakthrough. The theoretically determined uplift forces were generally within the same order of magnitude as the measured forces, though measurements exceeded theoretical values. This difference could be attributed to factors like mixture density and production speed, possibly influenced by measurement errors. It's crucial to recognize that this test did not fully validate the theoretical model, indicating the need for further investigation and refinement.
2. **Pancake diameter:** Feasibility of Increased Grain Size: The test unequivocally demonstrated that sand flow with an increased grain size is indeed feasible. The minimum required radius of 7.3 meters was successfully achieved during the tests, suggesting that larger grains can be effectively employed in sand flow applications without compromising the structural integrity of the system.
3. **Pancake development:** Our study employed conductivity probes to monitor sand pancake formation and evolution in real-time. We observed distinct phases, including the initial central crater, gradual closure, and eventual complete filling beneath the steel dragline mats. Figure 12 visually depicts these findings.
   The experiments revealed that the largest sand pancakes were formed under conditions characterized by relatively high mixture velocities and low sand concentrations. This finding suggests that controlling these parameters can be crucial for optimizing sand flow processes, particularly when larger grain sizes are used.

4. **Sand segregation:** Our examination of the trial pit and soil samples from the sand pancakes indicates a consistent pattern of material distribution throughout their depth. Notably, the uppermost 5-10 centimeters of the pancakes exhibit coarser particle prevalence. This phenomenon results from increased flow velocities and the subsequent washing out of finer particles near the tunnel element interface.
5. **CPT and relative density:** An important aspect of this study was the assessment of the relative density of the Kaliwaal sand pancakes. Based on the data obtained from the calibration chamber tests and penetrologger results, the estimated relative density of these sand pancakes was found to be less than 15%. This low relative density may have implications for the stability and behaviour of the sand pancakes in practical applications.

Overall, the results of the full-scale sand flow test provide valuable information for engineers and researchers interested in utilizing larger grain sizes in sand flow systems. The successful achievement of the required radius and the insights into sand pancake formation contribute to our understanding of the potential benefits and challenges associated with this approach. Additionally, the estimation of low relative density underscores the need for further research and consideration of factors that may affect the performance and stability of sand pancakes in real-world scenarios. This study serves as an important step toward advancing the field of sand flow technology and offers a foundation for future investigations in this area.

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