FUNDÃO MINE TAILINGS DAM FAILURE

This case study on the Fundão Mine tailings dam failure, has been prepared solely by GDS following its review and interpretation of the publicly available technical report. This case study briefly summarises some of the many geotechnical engineering findings reported by the panel. Specifically, it focuses on aspects of the advanced laboratory testing programme conducted during the investigation, which employed an advanced cyclic direct simple shear apparatus designed and manufactured by GDS Instruments.

Read below or download the case study PDF here (https://www.gdsinstruments.com/__assets__/WebPages/04640/Fundao-Mine-Tailing-Dam-Failure.pdf).

Introduction

At 3:45 pm on the 5th of November 2015, the 110 m tall Fundão Tailings Dam, located in the south-eastern Brazilian State of Minas Gerais, collapsed in a liquefaction flowslide. The failure released approximately 43 million cubic metres of iron ore tailings into the environment, polluting over 600 km of watercourses (Fonseca do Carmo et al., 2017) and resulting in 19 deaths. The event was considered to be Brazil's worst environmental disaster, and has to date cost the mine's owners billions of dollars (Ridley and Lewis, 2019).

The Fundão Tailings Dam Review Panel (the Panel) was assembled following the collapse to investigate and determine why the Fundão Tailings Dam (the Dam) failed in a liquefaction flowslide. The Panel reported on its findings (Morgenstern et al., 2016) on the 25th of August 2016, concluding that conditions necessary for liquefaction to occur within the Dam were present prior to failure (i.e., loose, saturated sand tailings were present), and that lateral extrusion of slimes-rich deposits underneath sand tailings provided the mechanism to trigger the liquefaction flowslide.

This case study briefly summarises some of the many geotechnical engineering findings reported by the Panel. Specifically, it focuses on aspects of the advanced laboratory testing programme conducted during the investigation, which employed an advanced cyclic direct simple shear apparatus designed and manufactured by GDS Instruments (GDS). We strongly recommend that our readers refer to the publically available Panel report, published by Cleary Gottlieb Steen & Hamilton LLP, for a detailed commentary on the Fundão Tailings Dam failure. Additional information relating to ongoing environmental impacts and legal cases are available within the wider media.

Figure 1: The Fundão Tailings Dam on the 7th of July, 2016, approximately eight months after failure occurred.
Source: "Mariana, Minas Gerais" by Ibamagov is licensed under CC BY-SA 2.0. https://www.flickr.com/photos/ibamagov/29702341695/in/photostream/

THE FUNDÃO MINE TAILINGS DAM

The Fundão Mine Tailings Dam was constructed to retain sand and slimes tailings that were produced from the benefication of iron ore. Transported in slurry form, the sand tailings (sands) comprised sand and silt-sized particles, which generally allowed for rapid water drainage following their deposition. The sands deposits were however typically loose and uncompacted, due to their placement by hydraulic means. The slimes tailings (slimes), also transported as a slurry, were classified as a low-plasticity clay (despite containing only a small proportion of clay minerals), which produced deposits that were more compressible and of lower permeability than the sands.

With two different material types to be retained, the initial Dam design used a ‘drained stack’ concept, as generalised in the Figure 2 schematic. This concept aimed to progressively stack the sands behind a Starter Dam, with the slimes retained behind the sand stack, and the Starter Dam raised on top of the sands using upstream-style construction. A critical condition of this design was to maintain adequate drainage within the loose, uncompacted sands, such that the sands remained unsaturated and did not become susceptible to static liquefaction. This condition was to be met through (i) construction of a high-capacity drainage system beneath the Starter Dam; (ii) construction of concrete galleries (2 m diameter conduits) beneath the left and right Dam abutments to convey upstream surface water inflow downstream of the Dam; (iii) separation of the slimes from the sands during tailings deposition by maintaining a 200 m sand beach width from the Dam crest, such that downward drainage in the sands was not impeded.

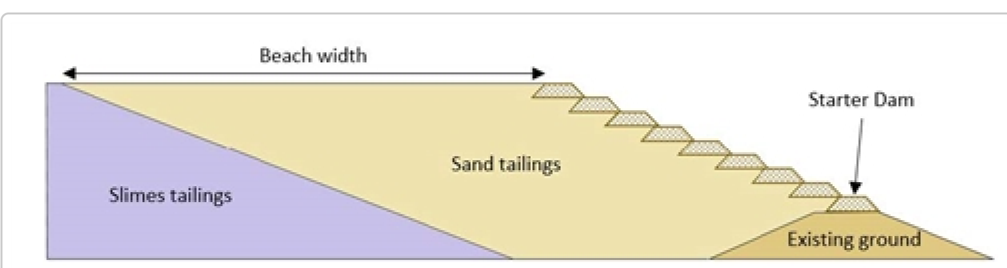

Figure 2: Generalised schematic illustrating the ‘drained stack’ concept.

Starter Dam construction, including that of the high-capacity drainage system and concrete galleries, was completed in October 2008. Tailings discharge then began in April 2009. A number of problems were however encountered during Dam operation and raising, prior to the November 2015 failure. These included:

- Serious construction flaws within the high-capacity drainage system, leading to an internal erosion incident in 2009. This resulted in the high-capacity drainage system being sealed off, and a revised drainage design eventually being implemented. Importantly, more widespread saturation of the sands was accepted following failure of the high-capacity drainage system.
- Difficulty maintaining the 200 m design sand beach width during 2011 and 2012, with the slimes getting as close as 60 m from the Dam crest. Importantly, this resulted in slimes being deposited in areas that were originally reserved for sands deposition.
- Structural failure of the concrete gallery beneath the left abutment, leading to the gallery being sealed off in 2013. Importantly, this resulted in subsequent construction of the left Dam abutment being shifted to an upstream alignment, closer to (and, in fact, above) areas in which slimes had been deposited.

It is also noted that three low-magnitude earthquakes (MW 1.8 to 2.6) occurred near the Dam approximately 90 minutes prior to Dam failure taking place.

PANEL INVESTIGATION INTO THE DAM FAILURE

Eyewitness accounts and physical evidence confirmed that the Dam collapsed in a liquefaction flowslide, initiating at the left abutment. This starting point led the Panel to focus on why a liquefaction flowslide occurred, why it initiated at the left abutment, and why it failed on the 5th of November 2015.

To answer these questions, the Panel undertook a systematic investigation, which required compilation of eyewitness interviews and Dam instrumentation data, analytical and seismological studies, and a virtual reconstruction of the pre-failure Dam structure. Estimation of the pre-failure engineering properties and performance of the Dam materials (i.e., sand and slimes tailings) were a fundamental input for the virtual Dam reconstruction. These estimations were largely based on subsurface field investigations and laboratory test data, the latter of which was predominantly obtained during a laboratory testing programme conducted by the Panel. This programme included advanced direct simple shear (DSS) and triaxial (TX) testing of specimens reconstituted/remoulded from shovel-excavated surface samples of sands obtained from the Dam site, as well as slimes obtained from the nearby Germano tailings impoundment.

ADVANCED LABORATORY TESTING PROGRAMME, INCLUDING USE OF GDS DIRECT SIMPLE SHEAR APPARATUS

a) Monotonic and cyclic direct simple shear (DSS) testing

Klohn Crippen Berger (KCB) performed 15 constant volume direct simple shear tests on sands and slimes specimens as part of the Panel's advanced laboratory testing programme. This testing was undertaken using a GDS Electromechanical Dynamic Cyclic Simple Shear (EMDCSS) device, which enables a constant specimen volume to be maintained during shearing (monotonic and/or cyclic) via a low compliance DSS device design, active height control, and physical lateral restraint via a stack of low-friction retaining rings (alternatively, a wire-reinforced rubber membrane may also be used). The tests were performed as per the ASTM D 6528 test standard (ASTM, 2007).

Figure 3: The GDS Electromechanical Dynamic Cyclic Simple Shear (EMDCSS) device.

Six slimes specimens tested by KCB within the GDS EMDCSS device were also nominally 70 mm diameter, and were consolidated across the same vertical effective stress range as applied during testing of the sands. Of the three specimens that were cyclically-sheared, one had an initial shear stress bias applied during consolidation (17.5% of the vertical effective consolidation stress), while one had cyclic loading applied following monotonic shearing to 20% shear strain.

Data recorded during the constant volume cyclic DSS tests showed that cyclic loadings representative of the low-magnitude earthquake shaking that preceded the Dam failure did not produce significant excess pore pressure build-up or shear strains. For example, applied CSR values of 0.01 tended to result in maximum shear strains of 0.01% being recorded within sand and slimes specimens after 30 loading cycles, while a CSR equal to 0.004 was estimated to be representative of an 84th percentile ground motion at a depth of 58 m below the Dam crest (near the base of sand tailings). Applied CSRs were subsequently increased during the cyclic DSS tests, where the CSR was raised to 0.05, and then 0.1.

Cyclic response of a clean sand specimen recorded during constant volume DSS testing conducted within the GDS office is presented in Figure 4 to illustrate typical cyclic performance of the GDS EMDCSS device. The test data and photos shown in Figure 4 are in no way related to the Fundão mine tailings dam failure investigation.

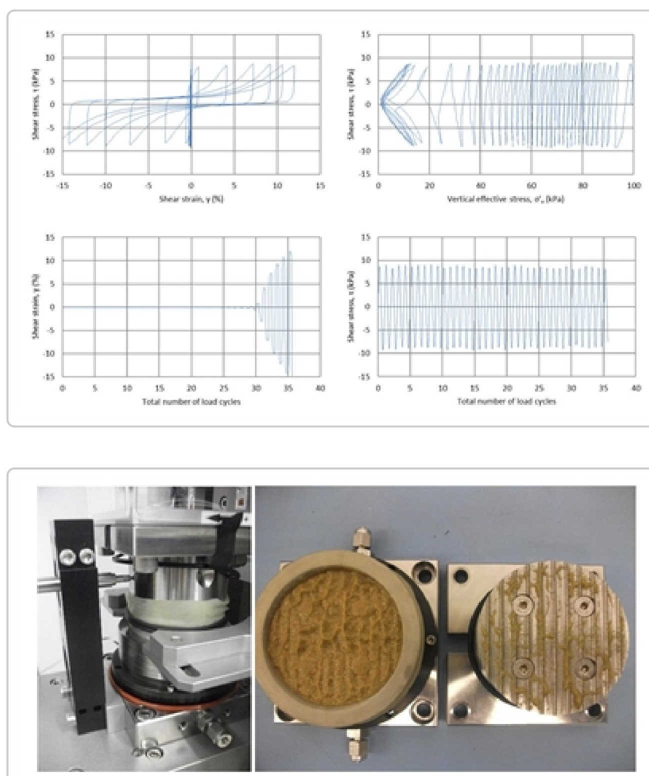

Figure 4: Cyclic direct simple shear response and photos of a clean sand specimen tested under

Data gained from the constant volume monotonic DSS tests produced estimations of peak undrained strength ratio (i.e., peak horizontal shear stress divided by vertical effective consolidation stress) in the range of 0.12 to 0.14 for the sands, and 0.16 to 0.17 for the slimes. It is noted that the sands specimens were estimated to have post-consolidation void ratios ranging from 1.04 to 0.93, while the slimes specimens estimated to have void ratios ranging from 0.99 to 0.91. All specimens demonstrated strain softening behaviour (i.e., a small to significant reduction in shear stress) when the soil was strained beyond the peak shear stress.

constant volume conditions within a GDS Electromechanical Dynamic Cyclic Simple Shear (EMDCSS) device at the GDS office. This test was in no way related to the Fundão mine tailings dam failure investigation, and is shown for illustrative purposes only.

b) Triaxial testing

An extensive series of drained and undrained triaxial (TX) tests was conducted on sands specimens by KCB during the advanced laboratory testing programme. A total of 21 tests were performed by applying strain-controlled compression to isotropically and anisotropically consolidated specimens under drained and undrained conditions, with results used to estimate strength parameters (e.g., an effective friction angle of 33°), as well as critical state line (CSL) and dilatancy parameters. These parameters subsequently formed an integral component of stability and deformation analyses conducted as part of the Panel's investigation.

Nine additional drained TX tests, termed 'extrusion collapse' tests, were also performed to investigate the possible initiation of liquefaction in the sands via a lateral extrusion mechanism (the mechanism is described further in the 'Conclusions' section of this document). To conduct these tests, specimens were firstly anisotropically consolidated, after which a specially-designed stress path was followed wherein the mean effective stress (i.e., specimen confinement) was decreased while the deviator stress was either kept constant or increased.

As the stress state of a test specimen neared the CSL, rapid specimen collapse was typically observed. This testing essentially replicated the manner in which the sands within the Dam failed on the 5th of November 2015.

It is noted that the TX apparatus used for performing 'extrusion collapse' testing is a modified TX system. The modifications are required to achieve the stress-control necessary to generate rapid specimen failure. GDS can provide TX devices specifically configured for 'extrusion collapse' testing, wherein a velocity-controlled triaxial load frame receives direct feedback from a triaxial load cell via a Digital Remote Feedback Module (DigiRFM). The direct feedback can significantly increase the responsiveness of the triaxial load frame, enabling fast axial compression to be applied as rapid specimen collapse initiates under drained conditions.

Undrained TX tests were also performed on slimes specimens obtained from field sampling, however the results from these tests were not used by the Panel.

c) Other advanced laboratory testing

One direct shear test, one oedometer test, and two bender element tests were conducted on sands specimens to provide additional strength, compressibility and permeability, and small-strain shear modulus estimates for the sands.

One oedometer test, one large-strain consolidation test, and one settlement test were conducted on slimes specimens to provide compressibility, coefficient of consolidation, permeability, and settlement rate estimates for the slimes. Please refer to Appendix D of the Panel's report for further details regarding these laboratory tests.

INSIGHTS FROM THE ADVANCED LABORATORY TESTING PROGRAMME

The Panel's advanced laboratory testing programme provided a number of important insights into the overall behaviour of the sands and slimes, as well as estimates for fundamental engineering parameters, which assisted the Panel in determining why the Dam failure initiated at the left abutment on the 5th of November 2015.

- Cyclic direct simple shear testing of sands specimens within a GDS EMDCSS device showed that significant excess pore pressures and shear strains did not develop when representative low-magnitude earthquake loadings were applied. This enabled the Panel to conclude that the earthquakes which preceded the Dam collapse did not induce liquefaction within the sands, ruling out a potential failure mechanism. The Panel did however note that the earthquakes likely accelerated the Dam failure.

- Drained 'extrusion collapse' triaxial testing of sands specimens replicated the rapid collapse that was observed to have occurred during the Dam failure, helping the Panel to confirm that a lateral extrusion mechanism ultimately triggered the liquefaction flowslide. Standard drained and undrained triaxial tests also provided strength, critical state, and dilatancy parameter estimates for the sands for use in stability and deformation analyses.

- Oedometer testing of a slimes specimen provided data to inform the consolidation and permeability parameters adopted as part of the Panel's modelling of the consolidation behaviour of slimes underlying the Dam's left abutment.

CONCLUSIONS REACHED BY THE PANEL

The Panel's investigation ultimately concluded that the Dam failed because a lateral extrusion mechanism triggered liquefaction within loose, saturated sands located at the left abutment. This mechanism, in which slimes-rich deposits located beneath the sands deformed laterally (i.e., were extruded) when compressed under the load from the increasingly tall Dam, forced the sands above to undergo a progressive reduction in horizontal stress (i.e., a reduction in confinement) and effectively loosen. This process eventually resulted in the sands reaching an unstable stress state, at which point liquefaction was triggered and the Dam breached. Modelling conducted by the Panel suggested this state of instability was expected to be reached at approximately the Dam height present on the 5th of November 2015, helping to explain why the Dam failed when it did.

Conditions necessary for a lateral extrusion mechanism to develop at the left Dam abutment and initiate the liquefaction flowslide were effectively created by problems encountered during construction, operation, and raising of the Dam.

Specifically:

i. Loose, uncompacted sands became susceptible to liquefaction through being saturated, which occurred due to inadequate drainage conditions. This issue is unlikely to have arisen had the original high-capacity drainage system remained operative throughout Dam operation.

ii. A lateral extrusion mechanism was able to develop because the abutment was realigned upstream and subsequently constructed above slimes-rich deposits. This realignment is unlikely to have been required had the underlying concrete gallery not experienced structural failure, and significant slimes-rich deposits are unlikely to have been present at the realigned abutment location had the 200 m design beach width been maintained throughout tailings deposition.

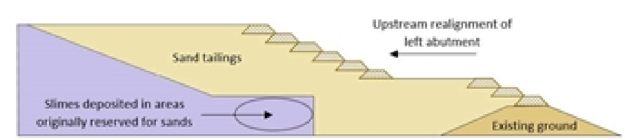

Figure 5: Generalised schematic illustrating how upstream realignment of the left Dam abutment, combined with encroachment of slimes into areas originally reserved for sands, could result in the left Dam abutment being constructed above slimes-rich deposits.

SUMMARY

The Fundão Tailings Dam was determined to have failed on the 5th of November 2015 in a liquefaction flowslide, initiated by the lateral extrusion of slimes-rich deposits underlying loose, saturated sand tailings. The Fundão Tailings Dam Review Panel reached this conclusion following a systematic investigation which, amid many other analyses, incorporated the advanced laboratory testing of sands and slimes specimens within a GDS Electromechanical Dynamic Cyclic Simple Shear (GDS EMDCSS) device. This case study demonstrates the insights advanced laboratory testing programmes can provide when examining the behaviour and potential failure mechanisms of tailings materials during forensic investigations, as well as how a chain of unintended events and deviations from original design can result in the catastrophic failure of a dam structure.

REFERENCES

- ASTM (2007). Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils. ASTM D6528-07. ASTM International.
- Fonseca do Carmo, Fl.; Kamino, L. H. Y.; Tobias Junior, R.; Christina de Campos, I.; Fonseca do Carmo, Fe.; Silvino, G.; Xavier de Castro, K. J. d. S.; Mauro, M. L.; Rodrigues, N. U. A.; Miranda, M. P. d. S.; Pinto, C. E. F. (2017). Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context. Perspectives in Ecology and Conservation, 15, p145-151.
- Morgenstern, N. R.; Vick, S. G.; Viotti, C. B.; Watts, B. D. (2016). Fundão Tailings Dam Review Panel, Report on the Immediate Causes of the Failure of the Fundão Dam. 25 August 2016. Cleary Gottlieb Steen & Hamilton LLP. http://fundaoinvestigation.com/the-panel-report.
- Ridley, K.; Lewis, B. (2019). BHP faces $5 billion claim over 2015 Brazil dam failure. Retrieved from https://www.reuters.com/article/us-bhp-brazil-lawsuit/bhp-faces-5-billion-claim-over-2015-brazil-dam-failure-idUSKCN1SD1AK.

Contact Info

GDS Instruments
Unit 32 Murrell Green Business Park
London Road
Hook
Hampshire
RG27 9GR
United Kingdom
+44 (0)1256 382450

info@gdsinstruments.com (mailto:info@gdsinstruments.com)