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# Matters arising in relation to "*The slip surface mechanism of delayed failure of the Brumadinho tailings dam in 2019*" by Fangyuan Zhu, Wangcheng Zhang & Alexander M. Puzrin

We are surprised by Zhu et al[1] (the Authors) concluding, based on numerical and analytical modelling combined with previously published data, "*that the Brumadinho catastrophe can be explained by the creep driven slip surface growth*". This Discussion explains why such a conclusion is not valid. We refer to the Author's figures as 'Fig 1' with new figures as 'Fig D1' etc.

## Lack of evidence for bonding in tailings from the Feijão dam

The authors follow Robertson et al.[2] and assume that the tailings particles were bonded by iron oxide (Fig 2a), and that such bonding endowed the tailings with added brittleness visible in triaxial response, drained (Fig 2b) or undrained (Fig 2c). An interpretation of cone penetration test (CPTu) and shear wave velocity $V_s$ data using empirical criteria[3] is claimed to show further evidence of microstructure.

The reality is different. The apparent bonding in Fig 2a does not allow inference of post-depositional developments because the tailings were a byproduct of complex metallurgical processing. Nothing in the SEM images allows the association of the occasional bonded grain occurrences with a post-depositional process instead of the previous metallurgical process. Note also that the unspecified post-depositional process that is purported to have generated bonding could not have acted similarly in the time-scale associated with laboratory testing of reconstituted specimens (hours or days) and in that associated with dam construction (years or decades).

Bonding must be demonstrated by mechanical tests. The drained triaxial data in Fig 2b corresponds to TX09 of Robertson et al., an initially dense specimen with shear localization evident in the test report. The boundary-measured response in Fig 2b cannot be identified with a material response. This is not generally the case for the more representative loose specimens, which typically show a near constant critical friction ratio ($M$) with no rupture of a cohesion-like component (Fig D 1).

The undrained brittleness in Fig 2c is a consequence of void ratio, not bonding, and readily computed by critical state theory. Reid et al.[4] examined the effect of moist tamping preparation procedures on subsequent undrained triaxial responses and found that much of the anomalously brittle undrained behaviour noted by Robertson et al. was potentially caused by a too-dense tamping process. This is illustrated in Fig D 2 which compares two specimens of B1 tailings sheared undrained from the same initial state parameter. The specimens tested by Robertson et al[2] – tamped initially into a denser state – show peaks that are not present in the specimens of Viana da Fonseca et al.[5], which were tamped loose.

Regarding the $V_s$ data, comparison with the database of Cha et al[6] shows no bonding[7]. Going further, if Robertson's[3] approach is applied as originally developed (i.e. using average site values) the Brumadinho tailings cluster with the uncemented dataset (Fig D 3).

## Lack of evidence for creep in tailings from the Feijão dam

The authors support a 'creep is essential' view based on results from two stages of a single triaxial test TXDW03 (Fig 2d) from Robertson et al.[2]. The procedures followed in that test are summarized in Table 1, including the names adopted by the authors for the two creep stages (“Test 1” and “Test 2”).

The authors calibrate the viscous component of their model to reproduce “Test 1” but not “Test 2”. As a justification, they state than $K_0$ = 0.5 is “closer to the loading conditions of the Feijão dam” than $K_0$ = 0.4. This is not plausible, as stress conditions close to a dam slope are highly non uniform[8]. Besides, the $K_0$ = 0.5 creep phase was performed drained whereas the $K_0$ = 0.4 creep phase was undrained; thus, the use of the $K_0$ = 0.5 creep results is not consistent with the authors’ assumption of undrained behaviour in the fine tailings.

The choice to calibrate with “Test 1” instead of “Test 2” seems important as the authors recognize (p.8) that if they calibrate the model on “Test 2”, the prediction of the time of failure would have been off by two years. The calibration presented would thus call into question the robustness of the model and its capability to act as a failure prediction tool.

Furthermore, the “creep” observed in test TXDW03 is credibly just an artefact of the testing procedure. We performed three triaxial tests on a stainless-steel block mimicking the conditions of test TXDW03:

1. Using a “thick” layer of silicone grease of approximately 0.5mm between the two latex membranes used for end lubrication
2. Identical to (1) but with “thin” layers of grease of less than approximately 0.2mm.
3. An additional test without latex membranes or grease,

When lubricated platens and latex membranes were not used, the test on the steel block showed no measurable displacements in time. Results for the other cases (Fig D3) suggest that a significant proportion of the creep reported for TXDW03 was viscous deformation/compression of the end lubrication (grease and membranes) rather than actual soil behaviour.

Arroyo & Gens[7] presented a complete and robust series of triaxial tests, investigating the effect of strain rate on undrained triaxial response. Those tests showed that strain rate had minimal effect on undrained response and, therefore, that viscous effects were negligible for Brumadinho tailings. That result is well aligned with the expected behaviour of non-plastic granular materials[9].

## Liquefaction physics and undrained strength degradation

It has been clear since ~1973 that liquefaction involves pore pressure generation during shear without degradation of the critical friction ratio[10], and various plasticity models are able to capture the process[11]. This widely held understanding makes the authors' adoption of a total stress approach very surprising. It is doubly surprising because the essence of the Feijão failure is the rapid transition from drained to undrained conditions; a total stress approach cannot address this kernel issue.

Lacking a physical basis for their model, the authors adopt unrealistic postulates. The uncoupled model of the authors uses a total stress approximation to undrained soil behavior. It is postulated that undrained shear strength reduces permanently, "*even after the excess pore water pressures have dissipated and locally failed tailings consolidated under the new load*". No evidence is provided to support this assumption.

It is known that fabric orientation along sliding surfaces in plastic clays is conducive to irrecoverable degradation of effective frictional strength to a residual value[12]. However, Feijão tailings are not plastic clays and their index properties are inconsistent with such behaviour[13].

Measurements of undrained strength are more relevant in this case. Experimental work on the behaviour of silts post-liquefaction[14] indicates unequivocally that undrained strength increases significantly after reconsolidation; as indeed expected from critical state theory. Even in plastic clays, if loose when initially sheared, undrained pre-shearing does not lead to undrained strength loss, and undrained strength recovers after shear-induced pore pressure dissipation[15, 16].

## Unconvincing validation

The failure mode predicted by the model (Fig. 6) indicates a failure surface emerging at the front below the starter dam and emerging at the rear more than 100 m behind the crest. Those features are not observed in the front or rear cameras that recorded the failure.

## Conclusion

We contend that the authors have not explained the Brumadinho catastrophe, as they

a) have relied on selective and flawed experimental evidence to calibrate their model
b) have adopted an unrealistic model of the mechanics involved
c) have not validated the model convincingly

Therefore, their conclusions as unsubstantiated~~.~~

## Data availability statement

Data available on request from the authors

## Tables

*Table 1 Summary of test stages adopted by Robertson et al. (2019) for dead load creep test TXDW03 and used to calibrate creep model by Zhu et al. (2024)*

| Test stage | Ramp duration (min.) | "Hold" duration (min.) | Deviatoric stress ramp rate (kPa/min.) | Final stresses (kPa) | Drainage condition | Name used for stage by Zhu et al. (2024) |
|---|---|---|---|---|---|---|
| Ramp to $K_0 = 0.5$ | ~165 | ~15 | 0.45 | $q = 75$<br>$p' = 100$ | Drained | - |
| Creep at $K_0 = 0.5$ | n/a | 4000 | n/a | $q = 75$<br>$p' = 100$ | Drained | Test 1 |
| Ramp to $K_0 = 0.4$ | ~23 | 0 | 1.10 | $q = 101$<br>$p' = 100$ | Drained | - |
| Creep at $K_0 = 0.4$ | n/a | 2500 | n/a | $q = 101$<br>$p' = 100$ | Undrained | Test 2 |

## Figures

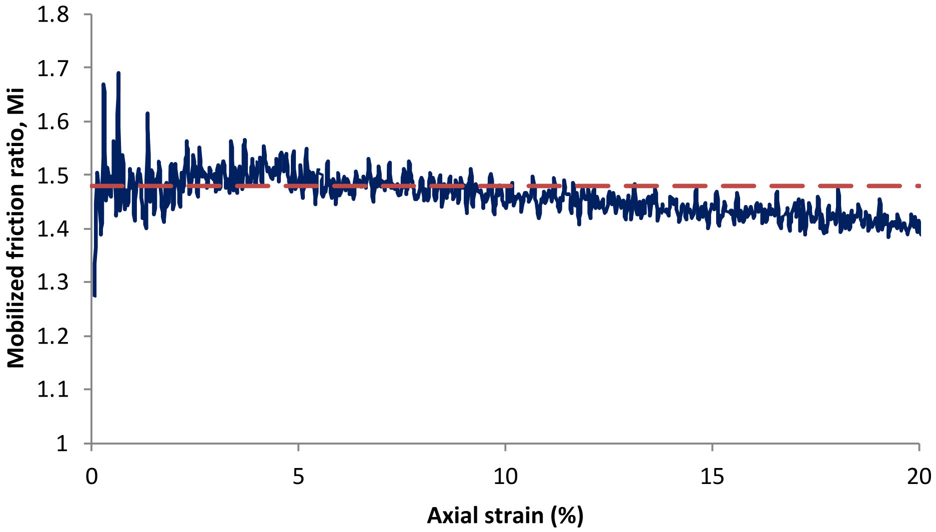

***Fig D 1 Mobilized friction on a drained triaxial test on loosely compacted ($e_0$ = 1.1) specimen of Brumadinho tailings (Arroyo & Gens, 2021; test BRUMA_R_S1_BL_CID_F_2)***

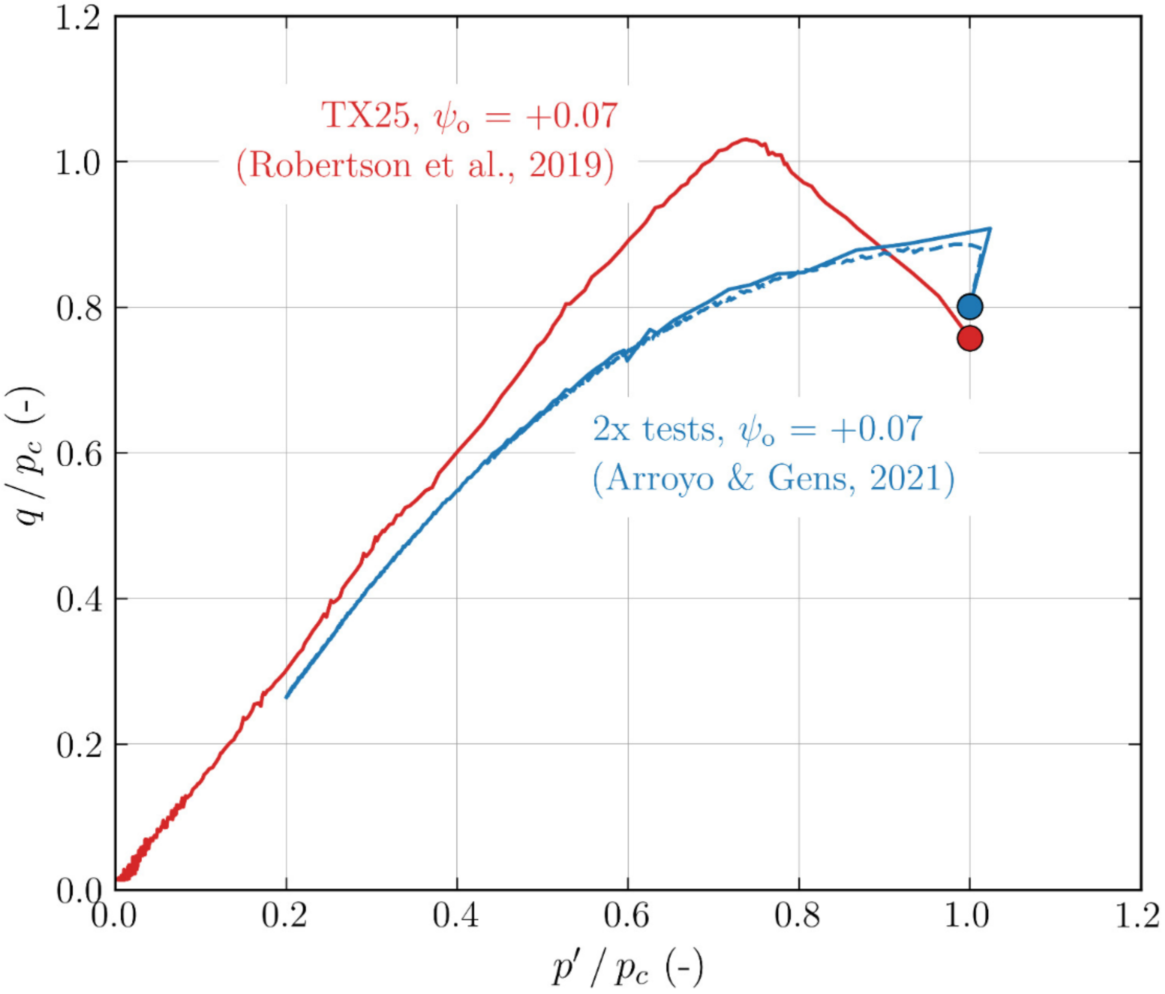

***Fig D 2 Comparison of anisotropically consolidated undrained triaxial tests by Robertson et al. (2019) and Arroyo & Gens (2021) on Brumadinho B1 tailings***

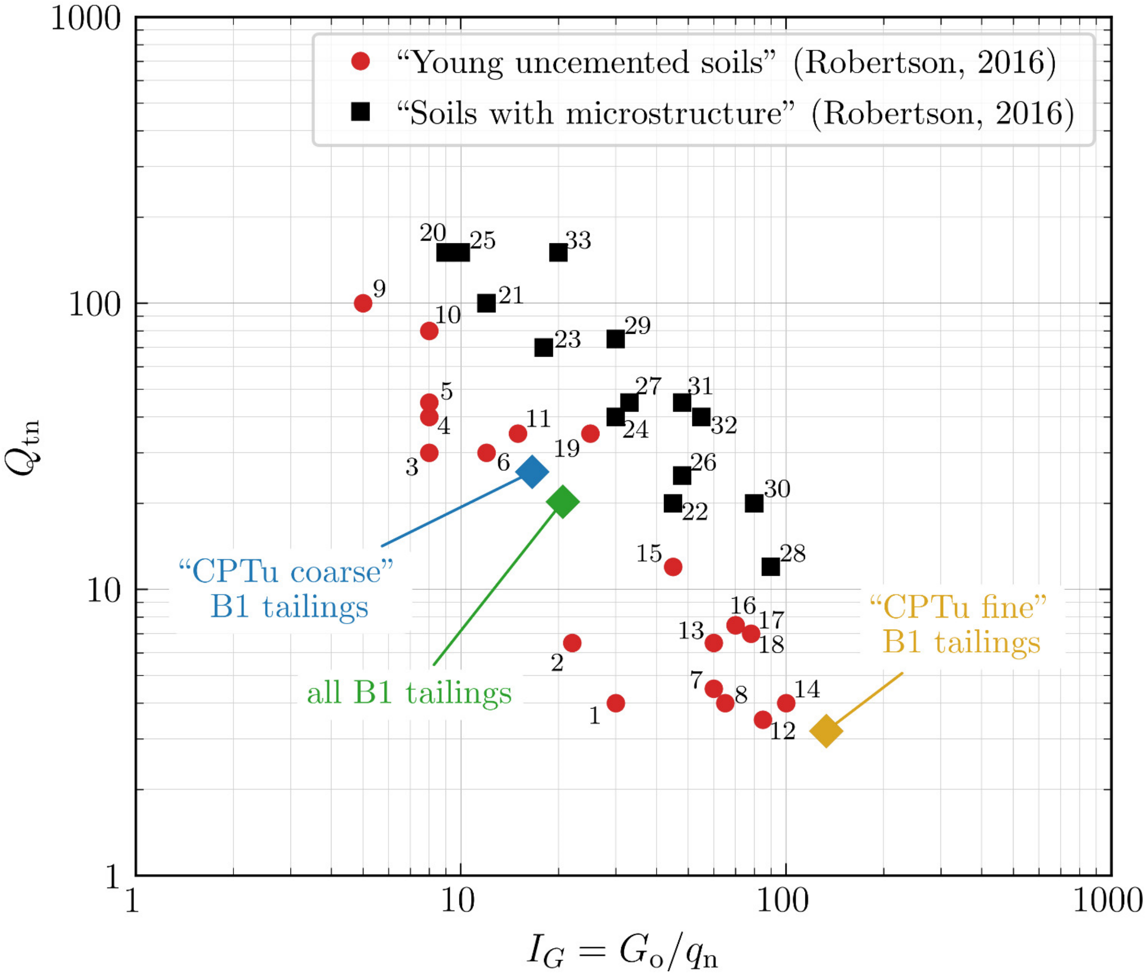

*Fig D 3  Average field data from Brumadinho dam B1 superposed on $Q_{tn} - I_G$ database from Robertson (2016). According to Robertson (2016) the red circles correspond to "young uncemented silica-based soils" and the black squares to "soils with microstructure or calcareous"*

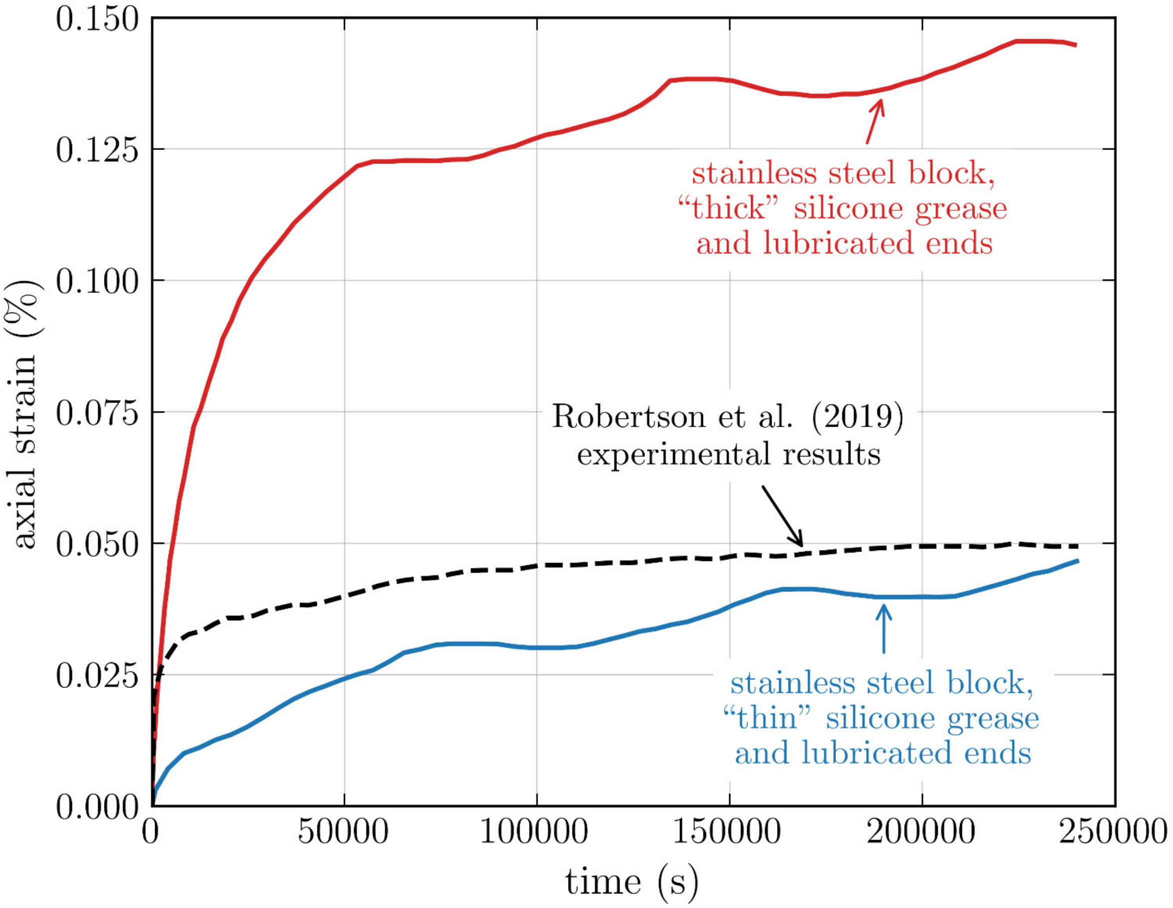

***Fig D 4 Externally measured displacements for tests on a stainless steel block tested on a triaxial cell using platens with lubricated ends. The stress condition was the same as in "Test 1" of the authors i.e $K_0$ = 0.5.***

## References

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