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Reply to: Creep deformation does not explain the Brumadinho disaster

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REPLYING TO Reid et al. *Communications Earth & Environment* https://doi.org/10.1038/s43247-025-02067-w (2025)

We are grateful to the discussers for giving us an interesting opportunity to validate the physical processes behind the Brumadinho dam failure. Detailed quantified analysis of their data confirms that the creep and permanent damage of microstructure are critical features of tailings behavior, which facilitated the formation and growth of slip surfaces and caused the dam collapse.

Microstructure and permanent damage

We understand the discussers' line of thought, but a quantitative analysis of Fig. 1 in Reid et al.[1] supports our conclusion that fine tailings do have some microstructure. We replot Fig. 1 from Reid et al.[1] in our Fig. 1, adding the contours of constant K_G^* from the original work of Robertson[2], where it has been shown that the only CPT results corresponding to young uncemented tailings (points 2, 3, 4 and 11) all fall within the range of $K_G^* = 100 - 200$. Incidentally, this is also where the coarse tailings of Brumadinho dam belong. The fine Brumadinho tailings, however, fall on the $K_G^* = 330$ line, which corresponds to ~10,000 years old sediments (mostly late Pleistocene; points 15–20) and marks the transition between light and strong bonding. It is difficult to find another explanation to why ~40 year old tailings would behave like a 10,000 year old sediment.

It is not, however, the CPT data alone that makes it difficult for us to ignore the existence of light bonding. There is a preponderance of evidence from multiple tests, which in contrast to the discussers' results in Fig. 2 in Reid et al.[1], do not suffer from sample disturbance. Both the historical laboratory data on intact block samples[3] and the in-situ vane shear tests[3] (Fig. 2) show signs of structural collapse and permanent damage. The highly brittle drop in shearing resistance in Fig. 2 is quite similar to that observed in Fig. 2b in the original paper (Zhu et al.[4]) and in many other drained triaxial tests[3] in fine and coarse tailings, while a sudden collapse of volume at 1% shear strain in the drained triaxial test TX14[3] demonstrates that some elements of microstructure can survive even in disturbed samples. Curiously, the discussers' insight that the sharp loss of shearing resistance may have occurred due to a shear band formation is consistent with our assumption that permanent damage takes place during localized intense shearing of fine tailings within narrow slip surfaces.

Effects of grease on the measured creep rates

Matters Arising present intriguing new data on the creep of grease and membrane at the ends of a steel block (Fig. 3 in Reid et al.[1]) and concludes that the observed creep of the tailings in Test 1 is almost solely due to the grease. Yet, a carefully quantified interpretation of this data indicates that grease had little effect on the observed creep rates.

Indeed, the grease in Fig. 3 in Reid et al.[1] exhibits an almost constant rate of creep, similar to Newtonian fluids, while the entire sample in Test 1 (tailings + grease at the ends) shows a slowly decaying creep, typical for granular materials under moderate deviatoric stresses[5]. Because the original axial strain from Test 1 (black line in Fig. 3a) is contributed by both grease and tailings, it must be corrected for the grease effects. However, even for the case of a "thin" grease layer in Fig. 3 in Reid et al.[1], such a correction would result in a rather unlikely behavior of tailings for K_0 conditions: after about 200 min, their height starts growing under the constant load (red line in Fig. 3a). Since the discussers used the same type of grease as Robertson et al.[3], their work suggests that the grease in Test 1 was so thin that it had a negligibly small non-decaying effect on the typical decaying creep of the tailings.

Incidentally, even if the grease were to exhibit a decaying creep, making it possible to mimic exactly the time behavior of the whole sample by adjusting the thickness of grease at the ends of the steel block, this would still not provide evidence that the tailings are rate independent. As shown in the Methods, this may simply mean that grease and tailings have the same relaxation times, confirming again the suitability of Test 1 for calibration of the creep models.

Rate dependency and creep

Another argument in Matters Arising against the creep in Brumadinho tailings is based on the perceived negligible strain rate dependency of shear strength in the nine K_0-consolidated undrained triaxial compression tests performed by Arroyo and Gens[6] for three different types of Brumadinho tailings (consistent with our assumptions, they used $K_0 = 0.5$). This argument is not valid for the following four reasons:

1. A closer quantification of the strain rate dependency in the Arroyo and Gens[6] tests in Fig. 3b, results in a non-negligible 2.5–4.5% increase of peak strength per log cycle of strain rate. Although it is slightly lower than in clays[7] (9–10%), it is higher than the rate dependency of the large strain strength of silty soils (1%-3%) measured in ring shear tests[8] and back-calculated from slow-moving landslides[9,10].
2. Multiple studies on sands reviewed by Augustesen et al.[5] have revealed that even when shear strength is indeed rate independent, the material

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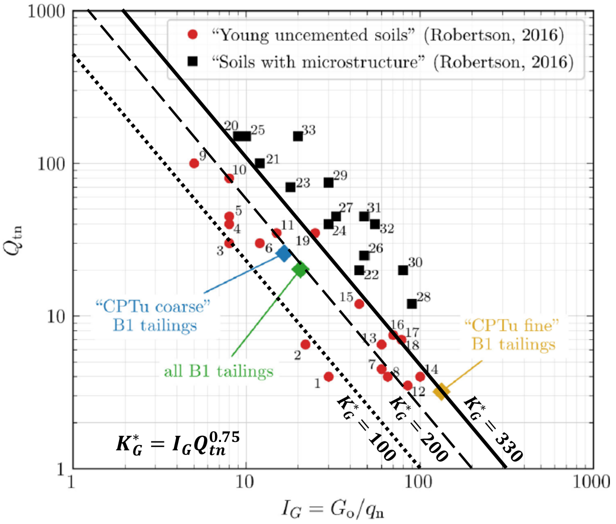

Fig. 1 | Evidence of microstructure in CPT results. Q_{tn} vs I_G chart to identify soils with microstructure (after Robertson[2]).

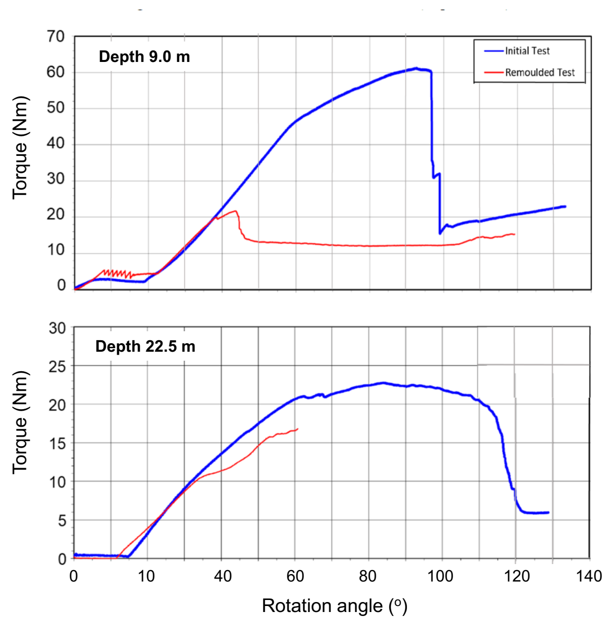

Fig. 2 | Evidence of microstructure in vane shear test results. Results of the vane shear tests VT-16-11 (Depth 9.0 m) and VT-16-12 (Depth 22.5 m) on the Brumadinho tailings (with permission, after Robertson et al. [3]).

will still experience creep. And it is the creep and not the shear strength rate dependency that is driving the slip surface growth.

3. The creep of non-clayey soils and tailings is a well-established and carefully studied[11–13] phenomenon, and it turns out that one does not need large creep rates to explain delayed failure three years after dam closure for a marginally stable Brumadinho dam. In fact, when the visco-elastic creep model calibrated using the Test 1 (black line in Fig. 3a) is subjected to a one-dimensional consolidation test, it produces a normalized secondary compression coefficient of $C_\alpha/C_c \approx 0.005 - 0.01$, which is at the lower bound of the range obtained from oedometer and field tests on tailings and other silty materials[14–17].
4. In fact, the failure of previous studies[6] to reveal the creep-driven growth of slip surfaces is not due to a low rate-dependency in the mechanical behavior of tailings, but rather the way it was modeled. Instead of accurately modeling the rate-dependency of stiffness, these studies[6] focused on the less relevant rate-dependency of strength.

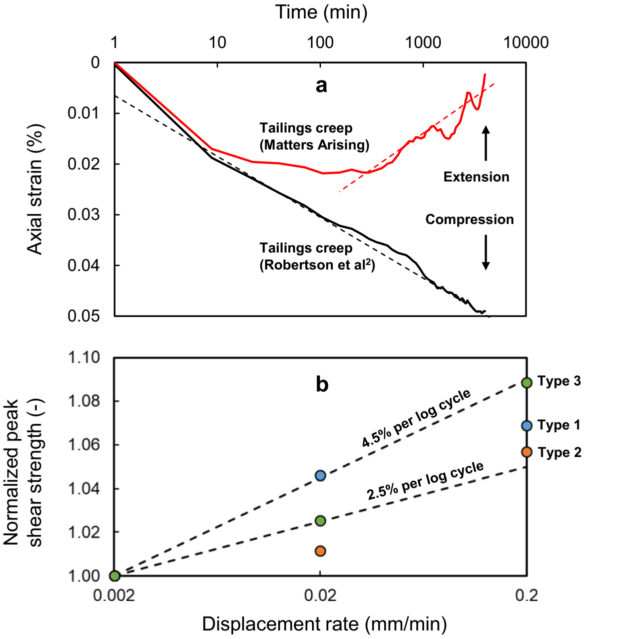

Fig. 3 | Rate dependent behavior of Brumadinho tailings. a Original axial strains in the Test 1 from Roberson et al. [3] (black line) and after correcting them (red line) for the creep of grease provided in the Matters Arising (Fig. 3 in Ried et al. [1]). The correction is performed by subtracting the creep of a "thin" grease layer (Fig. 3 in Ried et al. [1]) from the original axial strains of Test 1. **b** Strain rate dependency of the peak stress ratios q_p/p_p' in undrained triaxial compression tests for three types of Brumadinho tailings by Arroyo and Gens[6]. Peak stress ratios are normalized for each tailings type by the corresponding stress ratio at the slowest strain rate.

It follows that although the creep data of Robertson et al.[3] are not very extensive, they are consistent with the current state of knowledge and give no reason to worry about the excessive influence of grease. In cases where detailed creep data are unavailable, these rates can be used in a preliminary analysis of the long-term stability of tailings dams: if a dam fails at such relatively low rates, one should be concerned.

Modelling and validation

We understand and share the discussers' commitment to the principle of effective stresses. Many models, including the one used by Arroyo and Gens[6], can simulate well the generation of excess pore pressures during undrained shearing, with undrained shear strength fully recovering after the pore pressure dissipation. However, as the discussers mention, these models may not work for materials whose microstructure experiences permanent damage during undrained shearing, such as in the fine Brumadinho tailings. We overcome this limitation by employing a simple model where this permanent damage is imposed directly in the form of undrained shear strength degradation. Because the formation and fast growth of slip surfaces takes place under undrained conditions, both total and effective stress analyses produce identical results, provided one uses identical undrained shear strengths. Accounting for damage, however, is simpler within the total stress analysis, which explains our choice.

With respect to model validation, the images from the front camera in our Fig. 6 in Zhu et al.[4] confirm that the initial bulging of the dam slope took place right above the main slip surface predicted by our model. Concerning the slip surface emerging at a particular location at the rear, our numerical results (Fig. 9 in Zhu et al.[4]) show that two seconds after the onset of failure, multiple inclined shear bands appear within the dam body and it is difficult at present to predict reliably which one will occur first. This is not significant, however, because no matter where the first slip surface emerges behind the crest, retrogressive failure will eventually lead to the collapse of the entire tailings body.

Conclusions

Our work shows that the creep and permanent damage of microstructure are critical features of the tailings behavior facilitating the formation and growth of slip surfaces. We understand though that without suitable quantification it is easy to misinterpret even high-quality field and laboratory data and to overlook these important physical phenomena. Without accounting for them, even the most sophisticated constitutive models can produce a false sense of safety, concluding that some external actions are always required for an upstream dam to fail after its closure. Our paper confirms that this may not be the case, even for the relatively light bonding and low creep rates of the Brumadinho tailings. We hope that it will encourage the development of new approaches beyond the mainstream thinking.

Methods

Assume that both grease and tailings exhibit decaying creep described by a Kelvin-Voigt model[18]:

$$\varepsilon_{s,g} = \frac{\Delta h}{h_0} = \frac{q}{3G_g}\left(1 - e^{-t/\tau_g}\right);\ \varepsilon_{s,t} = \frac{\Delta H}{H_0} = \frac{q}{3G_t}\left(1 - e^{-t/\tau_t}\right) \quad (1)$$

where q is the constant deviatoric stress; h_0 and H_0 are the initial thicknesses of the grease and tailings, respectively; $\varepsilon_{s,g}$ and $\varepsilon_{s,t}$ are the shear strains, G_g and G_t are the shear moduli, τ_g and τ_t are relaxation times, subscripts "g" and "t" refer to the grease and tailings, respectively.

For $h_0 \ll H_0$, the creep of the entire sample is given by

$$\varepsilon_s = \frac{\Delta h + \Delta H}{H_0} = \frac{h_0}{H_0}\frac{q}{3G_g}\left(1 - e^{-t/\tau_g}\right) + \frac{q}{3G_t}\left(1 - e^{-t/\tau_t}\right) \quad (2)$$

Replacing the tailings by a rigid block with $G_t = \infty$ and changing the initial thickness of grease h_0 to h_{g0}, as carried out by the discussers, results in the creep rate of the entire sample (rigid block + grease):

$$\varepsilon_s = \frac{\Delta h}{H_0} = \frac{h_{g0}}{H_0}\frac{q}{3G_g}\left(1 - e^{-t/\tau_g}\right) \quad (3)$$

This can be adjusted to mimic exactly the response of the entire sample with grease and tailings in Eq, (2) in two cases only: (i) when $h_{g0} = h_0$ and $\tau_t = 0$, i.e., when the tailings are indeed rate independent, or (ii) when

$$h_{g0} = h_0 + H_0\frac{G_g}{G_t}\ and\ \tau_g = \tau_t \quad (4)$$

i.e., when the grease used by discussers is thicker than the one in the original Test 1, while the tailings and the grease are both rate-dependent with the same relaxation times, which would be ideal for any experiment aiming to correctly calibrate creep rates.

Similar conclusions are valid for a generalized Kelvin-Voigt model with n elements, where the creep responses of tailings and grease are given by Prony series:

$$\varepsilon_{s,g} = \sum_{i=1}^{n}\frac{q}{3G_{g,i}}\left(1 - e^{-t/\tau_{g,i}}\right);\ \varepsilon_{s,t} = \sum_{i=1}^{n}\frac{q}{3G_{t,i}}\left(1 - e^{-t/\tau_{t,i}}\right) \quad (5)$$

allowing for simulating practically any experimental decaying creep curve. In this case, the perfect match between the tailings and the rigid block tests is achieved when

$$h_{g0} = h_0 + H_0\frac{G_{g,i}}{G_{t,i}};\ \frac{G_{g,i}}{G_{t,i}} = const\ and\ \tau_{g,i} = \tau_{t,i},\ for\ i = 1, \ldots, n \quad (6)$$

which is a generalized form of Eq. (4). It follows that even when the grease can mimic the entire sample response perfectly, this does not provide a unique proof of a rate independent behavior of tailings, as erroneously concluded in the Matters Arising.

Data availability

Data sharing not applicable to this article as no datasets were generated during the current study. All data needed to evaluate the conclusions in the paper are present in the manuscript.

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Author contributions

F.Z., W.Z. and A.M.P. co-wrote the Reply. AMP wrote the Methods section.

Competing interests

The authors declare no competing interests.

Additional information

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