

Discussion: Silt and its misrepresentation on the conventional plasticity charts

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This is a discussion piece on Barnes GE (2025) Silt and its misrepresentation on the conventional plasticity charts. *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering* 178(6): 710–721, <https://doi.org/10.1680/jgeen.24.00376>.

Dr Barnes is commended on his clear and insightful paper on silt and how it is misrepresented on conventional plasticity charts. Dr Barnes ably describes the difference in the nature and behaviour of silt compared with clay, and of the critical effect of the clay content and mineralogy on the behaviour of clay/silt/sand mixtures. In this context the authors have noted with concern that, in practice, geotechnical investigations sometimes do not differentiate between silt and clay, as if they are comparable materials or can both be considered as exhibiting plastic behaviour, despite a long history of silt being a distinct and problematic material (e.g. Proctor and White, 1977). Testing for grain size distribution is sometimes limited to coarse fractions only, even in soils that have significant fines content and where the relative quantity and nature of the silt and clay fractions are determinative of the behaviour and properties of the soil. The authors have seen little evidence of the reporting of results of the simple field testing of fine-grained soils covered in clause 34.3 of BS 5930 (BSI, 2015). Where testing for Atterberg limits is carried out, which is not a given, the soil descriptors are typically based on the conventional plasticity chart that Dr Barnes shows can be misleading; or worse, the Atterberg limit test data is ignored, and the soil description is based solely on proportions of constituent materials from particle size distribution testing. In the authors' opinion, there is often a lack of understanding of the difference between silt and clay, their relative influences on soil behaviour and of how critical this difference can be for construction.

Dr Barnes briefly mentions some engineering issues related to silt, in general terms. To add to this, reference is made here to catastrophic failures of tunnels in various soils, including silt or sandy silt.

The problem of tunnelling in silt below the groundwater table was well understood when tunnelling was carried out with an open face: the face could be dry and stable on initial excavation but would then deteriorate into 'flowing ground' as defined by Terzaghi (1950), potentially resulting in complete inundation of the constructed tunnel. Golder Associates (1976) suggested that the lower boundary for potential flowing behaviour is an

effective grain size of 0.005 mm. The 'effective' grain size is taken as where 10% of the sample by weight is smaller, based on Heuer (1974), noting that 0.005 mm is close to the silt/clay boundary of 0.002 mm. The widespread use of pressurised tunnel boring machines (PTBMs) and segmental tunnel linings has largely eliminated the concerns with, and possibly understanding of, risks associated with tunnelling in silt and related soils. While the use of PTBMs and segmental tunnel linings have proven generally effective in silt and clay/silt/sand mixtures, there have been some rare, but generally catastrophic, failures that are often associated with tunnelling in those soils. More frequently, misunderstanding the influence of the relative proportions of silt and clay and their behavioural influences can result in excess ground losses, settlement and sinkholes due to tunnelling or excavations.

In 2003 there was a massive tunnel collapse during the construction of Metro Line 4 in Shanghai, China (Tan *et al.*, 2020). The collapse occurred while constructing a cross-passage between two parallel PTBM-excavated and segmentally lined tunnels. The collapsed started when previously frozen ground thawed due to equipment failure (Tan *et al.*, 2020). The initial collapse propagated into a sequential failure of both tunnels over a length of 238 m for each tunnel. The cross-passage was being excavated in soil unit 7-1 that Tan *et al.* (2020) describe as sandy silt. The grain size distribution for unit 7-1 from Tan *et al.* (2020) is reproduced in Figure 1. The consequences of the collapse in Shanghai were catastrophic, with a sinkhole above the collapse estimated at over 20 000 m³. Several large buildings had to be demolished as a result, although luckily no one was injured. When the tunnels were excavated for reconstruction, by cut-and-cover, it was found that, in some places, the segmental lining had changed from a circle to two parallel lines, like a sandwich, as shown in Figure 2 (after Zheng *et al.*, 2017). The collapse in Shanghai, and other tunnel failures including Kaohsiung in 2005, Nanjing in 2007, Tianjin in 2011, Foshan in 2018, Shanghai Line 18 in 2019 and Nak-Dong in 2020, resulted in a steady stream of research into what the researchers termed 'water-soil gushing' (WSG), their term for Terzaghi's flowing ground. Shirlaw *et al.* (2025) summarised 13 major WSG failures, all of which involved collapse of or severe damage to multiple rings of the segmental tunnel lining. Of the 13 WSG failure cases, seven required the replacement of over 100 m of completed, segmentally lined tunnel. In five cases both parallel tunnels were badly damaged or

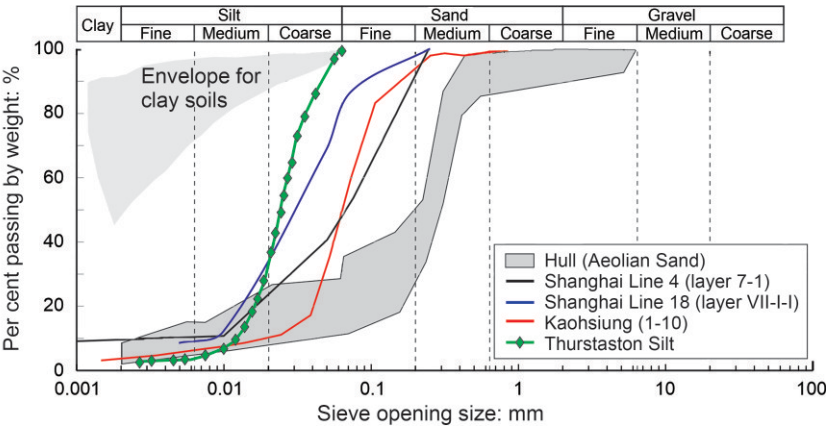


Figure 1. Grain size distribution curves for soils where water-soil gushing failures were initiated (source: Shirlaw *et al.*, 2025). Superimposed data from Barnes (2025): Oakdale, Purafllo, Kaolin, London, Illite, KM1 and KM2 clay samples shown as an envelope and the Thurstaston Silt shown separately. KM1 and 2 clays refer to laboratory prepared clays, see Barnes (2025)

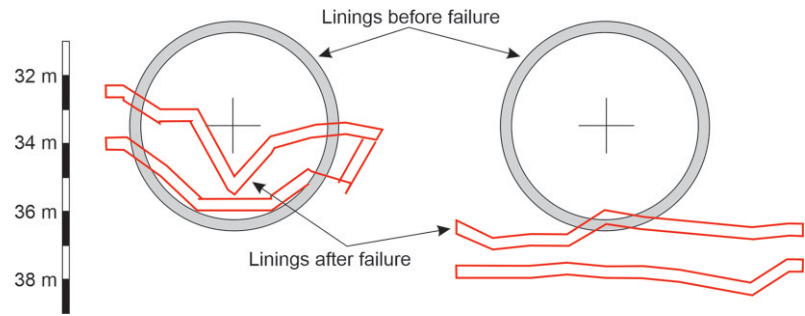


Figure 2. Failure of two parallel running tunnels, Shanghai Metro Line 4 (source: Zheng *et al.* (2017))

collapsed for more than 100 m, mostly more than 200 m. The failures include some of the largest soft ground tunnelling failures of the last 35 years. There are published case studies for most of the failures, with the majority occurring in soil described as silt, sandy silt or silty sand as summarised in Table 1.

Few of the case studies provide grain size distribution curves, and even fewer include information on plasticity. Four grain size distributions from tunnel collapse case histories are summarised in Figure 1: for Hull in 1999, Shanghai Line 4 in 2003, Kaohsiung in 2005 and a smaller failure during the construction of Shanghai Line 18 in 2019. For context in respect of Dr Barnes’ paper, the grain size distribution for the Thurstaston Silt and a range of clay soils are also shown in Figure 1. The soil at the point of initial failure for Hull was sand, some silt to silty sand, and for Shanghai Line 4 was

described as a sandy silt by Tan *et al.* (2020). The critical soil type for Kaohsiung was described by Lee and Ishihara (2011) as silty sand but was at the borderline between fine- and coarse-grained soils based on the Unified Soil Classification System. Although the soil in the Shanghai Line 18 failure was described as sandy silt by Zhang *et al.* (2021), the proportion of sand was very small. Not shown in Figure 1 is the data for the silty sand involved in a failure in Taipei in 1994, given simply as clay (6%), silt (14%) and sand (80%) content. Limited information was provided on Atterberg limits other than that the soils for Shanghai Line 4 and Kaohsiung were non-plastic. A pinhole test carried out after the failure of the Kaohsiung tunnels (Lee and Ishihara, 2011) showed that the soil was erodible. However, the standard for the test, the American Society for Testing and Materials’ (ASTM) D4647 (ASTM, 2020), states that there is no need to use the test for soils with a plasticity index of <4% and with <12% of particles smaller than 0.005 mm, as such soils generally have low resistance to erosion. The tested soil at Kaohsiung met both criteria.

Table 1. The descriptors used for the soils at the point of failure, 13 failures cited by Shirlaw *et al.* (2025)

Silt	Sandy silt	Silty sand	Sand	Sand and gravel
1	4	5	2	1

The range of grain size distributions that turned into flowing ground can be seen in Figure 1, and particularly that, except Hull, the curves show a large silt content but small clay content. The

published data on grain size, available for five of the 13 cases, consistently showed that the clay-size particle content was less than 10% for the soils which were the immediate source of the failure. References to the case studies and related research are provided in the discussion contribution by Shirlaw *et al.* (2025) and are not replicated here unless specifically referenced. From the various studies, erodibility of the soil was clearly a key factor in the failures, see Qin *et al.* (2022) and Sturt *et al.* (2025). There is some critical or gradational threshold for clay mineral content for which the propensity for erodibility and flowing ground diminishes or is effectively inhibited and this transition bears further research and characterisation. Clearly, however, measuring only the total ‘fines content’ and using this metric as a guide toward ground behaviour is misleading. This shows the importance of Dr Barnes’ work on the identification and behaviour of silt and clays/silt/sand mixtures.

The d_{95} value of the soil is also likely a factor in the failures: if there is a small leak in a tunnel lining or the joints between the segments, silt particles can be carried into the tunnel through a very small opening, <0.2 mm. Coarser-grained soils require a larger opening for the soil particles to be carried into the tunnel without the particles blocking the opening. This may be a factor at the leading edge of the sequential tunnel lining failure, and therefore in the extent of the failure.

The soils from the WSG failures shown in Figure 1 are poorly graded, and this is likely a further factor in the failures. No mention of gap-graded soils was found in the case studies of the 13 failures. Other factors in the failures, such as lining design, bolt and gasket details, hydraulic gradient and stress redistribution are discussed in some of the referenced studies. Although these factors can precipitate development of the initial openings through which ground flows, or exacerbate the severity of flowing ground, in the authors’ opinion these factors are not materially relevant for gauging whether ground below the water table can develop dangerous flowing behaviour.

The published studies on WSG failures have included cases studies and the results of numerical and/or laboratory modelling, for example Zheng *et al.* (2021), Zheng *et al.* (2023), Greene *et al.* (2024) and Sun *et al.* (2025). The focus of the modelling has been on the structural and hydraulic issues involved in the failures. The published studies confirm that a major factor in the failures was the ready erodibility of the soil(s) present. Once the failure is triggered by an initial loss of ground (see Shirlaw *et al.* (2025) for examples of triggers), erosion of the soil around a tunnel lining ring leads to movement, distortion and can, finally, lead to collapse of that ring. Prior to complete collapse, distortion of the ring and/or differential movement between adjacent rings will open gaps between the gaskets on the longitudinal and/or circumferential joints. Sturt *et al.* (2025) in their investigation of the Nak-Dong collapse show that the gaskets lost contact at a value for ring distortion that was much lower than the value required for lining collapse. Only about 10% of the replaced rings at Nak-Dong fully collapsed but many more exhibited severe distortion, with differences in movement between adjacent rings that resulted in gaps

between the rings and not just the gaskets. Leakage of ground water, and then water and soil, would occur well before final collapse of the lining. Where the movement was sufficient to allow soil and water to flow into the tunnel, further loss of ground and erosion would cause the adjacent ring to distort, followed by leakage, erosion and distortion of multiple rings in sequence.

Many of the modelling studies report the behaviour as specific to sand, particularly fine sand, even though the field data shows that silt and sandy silt are also implicated. Within the reported field failures, sand and silt behaviour are approximately equally represented and both are erodible. Dr Barnes’ study is consistent with the field reports and helps to dispel a perception in many laboratory-based studies that erodibility and related WSG (or flowing ground) behaviour is solely or primarily a sand-related problem. While the dangers associated with sand and silt were identified decades ago by Terzaghi (1950) and Heuer (1974), Dr Barnes’ work helps provide additional quantitative evidence and laboratory testing guidance that are sorely needed.

The information from the relatively small number of major WSG failures shows that a wide range of soils, from silt to sand and gravel, have been involved in such failures. However, the information from the field cases is too sparse to allow identification of the boundary between soils where WSG failures can occur, and those where they cannot. In this context, Dr Barnes’ paper appears to provide a basis for an initial identification of the boundary for clay/silt/sand mixtures, as shown in Figure 7(c) of his paper, and in the referenced paper by Gibbs (1962). This information can be added to the guidance given in AASTM D4647 (ASTM, 2020): that a silt or sand or clay/silt/sand mixture that is non-plastic or has a plasticity index of less than 4, and with <12% weight of particles <0.005 mm, is generally erodible. While the ASTM standard advises that the use of the pinhole test is not applicable to such soils, Dr Barnes advises that ‘For soils with high Silt contents the liquid and plastic limit tests are impracticable and unrealistic for the accurate determination of low plasticity indexes’ (Barnes, 2025, p. 719). Relying on low values for plasticity index alone to assess erodibility is therefore questionable.

Dr Barnes advises that manual/visual tests, as described in standards ISO 14688 (ISO, 2017a, 2017b), ASTM D2488-17 (ASTM, 2017) and BS 5930:2015 (BSI, 2015) should be used to define the clay/silt boundary. This raises the issue of whether it is appropriate to assess the erodibility of predominantly fine-grained soils with a direct test, such as the pinhole test, or to rely on the manual/visual tests. Further research that calibrates the results of pinhole tests with the qualitative behaviours observed using the manual/visual tests of the clay/silt boundary should be useful in this context.

Based on the evidence summarised above, it is suggested that a basis for testing erodibility or propensity for development of flowing ground in predominantly fine-grained soils could be as follows.

- (a) For soils that are non-plastic, assessed from the manual/visual tests, this information is sufficient to show that the soils are potentially erodible.
- (b) Soils that have a liquid limit >30% or plasticity index >12 are not usually significantly erodible by natural groundwater flow.
- (c) Soils between categories 1 and 2 may or may not be erodible, and the manual/visual tests of ASTM D2488-17 (ASTM, 2017) and BS 5930:2015 (BSI, 2015) should be employed to assess whether the soil exhibits clay behaviour, silt behaviour or is in the less predictable clay to clayey silt transition. The authors suggest that soils in the clay to clayey silt transition be subject to the pinhole test to ASTM D4647 (ASTM, 2020) to assess erodibility and susceptibility to flowing conditions.
- (d) Given that the results of the testing of soils with a high silt content and low values of plasticity index are unreliable, the advice in the ASTM Standard that pinhole tests need not be used for soil with a plasticity index <4 can be ignored.
- (e) Grain size distributions used to supplement the above tests should always include mechanical and hydrometer tests (ASTM, 2021) where the percentage of fines exceeds 20%.

The basis given above would not be applicable to saprolites where the natural soil contains a significant proportion of clay and silt but the fines are agglomerated. For example, it is known that completely weathered granite is readily erodible and can behave as flowing ground (Shirlaw *et al.*, 2000), although the liquid limit may be over 30%. Pinhole tests carried out on reconstituted samples of completely weathered granite would also not be representative of field behaviour, due to dispersion of the agglomerations during sample preparation.

In the authors' opinion, Dr Barnes' paper is a welcome call to arms for more rigorous soil logging and testing, to be used as a basis for behaviour-based descriptions and classification of silt soils. It highlights the importance of silt, which is often treated as an orphan child inconveniently between clay and sand. The authors also note that the forensic studies of the major tunnelling failures referenced here often provided limited useful information on the soils involved, other than a geological section. The emphasis has generally been on sophisticated laboratory and numerical modelling with limited information on the ground conditions and how to evaluate it for design, construction or forensic purposes.

A response to this discussion can be found at Barnes GE (2026) Response to discussion: Silt and its misrepresentation on the conventional plasticity charts. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, 10.1680/jgeen.26.00023.

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