論文 / 著書情報
Article / Book Information

Title	Assessment of standard research sand for laboratory testing
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Citation	Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 40, No. 1, pp. 93-103
Pub. date	2007, 2
Note	Quarterly Journal of Engineering Geology and HydrogeologyVol. 40/2007http://dx.doi.org/10.1144/1470-9236/06-017 (c) Geological Society of London 2007.
Note	This file is author (final) version.

Assessment of standard research sand for laboratory testing

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ABSTRACT: Standard soils are used worldwide as reference materials with which new model or single element experiments may be performed, assessed and calibrated. The testing databases associated with these are valuable resources that are particularly important when developing new procedures. However, the finite extent and variability of all natural deposits creates the possibility that standard soils may vary, or become unavailable, over time. The Ham River Sand (HRS), from the Thames Valley in the UK has been researched continuously and comprehensively in a series of studies since the 1940s, leading to a large database that includes recent advanced hollow cylinder, stress path triaxial and dynamic testing. Fresh samples are now unavailable and the paper describes a study of alternative sampling sources within the Thames Valley. Microscopic visual inspections, index measurements, direct shear, high pressure oedometer, bender element and stress path triaxial test data are presented in the paper, focusing on the natural variability and the ranges seen in material test response. A replacement for the original HRS is identified, so allowing those developing new tests the possibility of conducting experiments on material that is compatible with the existing HRS database. Reference is also made to advances in bender element testing achieved as part of the study.

KEYWORDS: laboratory tests, quarries, sand, stiffness & strength

Quarterly Journal of Engineering Geology and Hydrogeology, 40(1), 93-103, 2007.

Original URL:

http://dx.doi.org/10.1144/1470-9236/06-017

Introduction

Continuous access to standard test sands is essential to geotechnical researchers. However, such continuity is often hampered by the variability and finite size of suitable natural sand sources. The Ham River Sand (HRS) was quarried originally from one of the Thames River terraces at Ham, a site near Richmond Surrey lying about 12km south west of Heathrow Airport and the Staines Reservoir. Batches of 'sharp' HRS graded for use in building mortars were selected by Skempton and Bishop for use as standard research sands, and they have been used for this purpose at Imperial College London, and elsewhere, for almost 50 years. However, the operational lifetime of such quarries may be limited to just a few years in the Thames Valley and the Ham pit closed many years ago. A large database of HRS laboratory tests exists (e.g. Cornforth 1964, Green 1971, Reades & Green 1976, Symes *et al*. 1984 & 1988, Shibuya & Height 1987, 2003a & 2003b), making it vital to maintain continuity by locating a similar replacement. A substitute, termed the new Ham River Sand was located by the second Author (aided by Walker 1991), from a pit south of Heathrow near Chertsey (see Fig. 1) but this pit has also closed. A considerable body of data has been obtained since (e.g. Porović & Jardine 1994, Kuwano *et al*. 2000), making the Chertsey sand a significant test material in its own right.

This paper describes how a suitable replacement sand was selected by studying samples from several commercial pits working in the middle Thames Valley. Geological screening of the Thames terrace sequence and discussions with aggregate producing companies led to attention being concentrated on mid-Thames terrace samples from Eton, Poyle, Shepperton and Stanwell. As identified in Fig. 1 the latter three sites are all within 6 km of the Chertsey source. The Eton sand was excavated from a more distant site near Junction 6 of the M4 Motorway. This was taken from the Slough, Windsor and Maidenhead Flood Alleviation Scheme before being graded and stock piled near the Queen Mary Reservoir. Samples from these four most promising candidate sites were assessed for particle size distribution, particle roundness and sphericity, all of which affect mechanical behaviour. Direct shear box, oedometer compression, bender element and stress-path triaxal tests were then conducted on the most promising sands. The comparisons involved new and recent tests on the Chertsey sand and historical data on the original HRS. No fresh samples of original HRS are available today.

River Terraces

The lower Thames was diverted into its modern-day valley in the period between the Anglian glaciation and the Devensian Stage in the Pleistocene period of the Quaternary. The River Terraces mainly consist therefore of Post-Anglian, Pre-Devensian deposits. The first terrace is the youngest river terrace formed by the post-diversionary River Thames and its tributaries (Sumbler *et al*. 1996).

The original HRS was on the Kempton Park Gravel as is the Shepperton pit, while Chertsey, Eton and Polye are on the Shepperton Gravel (first terrace) and Stanwell is on the Taplow Gravel (third terrace) as shown in Fig. 1 and Table 1 after British Geological Survey (1998, 1999). The Shepperton Gravel, also known as Lower Floodplain Terrace, was formed in the period of 25 to 13k years BP in the Devensian Stage. The Kempton Gravel (Upper Floodplain Terrace) and Taplow Gravel were deposited about 100k and 200k years BP in the Anglian glaciation, respectively (Sumbler *et al.* 1996). These terrace deposits are naturally non-homogenous; the photograph in Fig. 2 shows sand and gravel layers alternating rapidly within a single terrace. The 'sharp' mortar sands taken from the quarries are industrial products graded and mixed from such profiles.

Sand Particle Properties

The initial study focused on just the fraction of particles that passed the 600μm-sieve. The resulting particle size distributions are plotted in Fig. 3, for the four 'new' sites together with the Chertsey curve and the upper and lower limits applying to the original HRS. The candidate curves are all slightly different from those for the original HRS and Chertsey sand, so only the fraction of particles that pass the 425μm-sieve (British 36-sieve) and are retained on the 180μm-sieve (British 85-sieve) were used for all the subsequent mechanical tests.

Figure 4 shows microscopic photographs of the particles passing the 600μm-sieve; an image of the Toyoura sand particles is also shown for reference. The sands all consist predominantly of quartz; those from Chertsey, Eton, Shepperton and Stanwell show a similar degree of brown iron oxide staining, while the sand from Poyle is paler. A range of suitable particle geometrical classification parameters has been proposed (Pettijohn 1975, among others); roundness is often assessed by comparison with standard images. Shape (form) can be characterised by sphericity indices (Zingg 1935, Sneed & Folk 1958, among others). Several other geometrical assessment techniques have been proposed recently including roundness from two-dimensional image analysis (Thomas *et al.* 1995, Bowman *et al.* 2001, among others). However, in this case a visual comparison chart by Powers (1982) was used that combines roundness and sphericity assessments. Here "Roundness" is defined as the degree of abrasion of a clastic particle as shown by the sharpness of its edges and corners and "sphericity" is defined as the degree to which the shape of a particle approaches that of a sphere. In other words the former is used for the local roundness of a particle while the latter is for the global roundness. For each sand around 400 particles were examined under the microscope, leading to the bubble charts, plotted in the sphericity-roundness plane, in Fig. 5. The largest bubbles indicate each sand's most characteristic sphericity-roundness point and the bubble size represents frequency of occurrence of the sphericity-roundness point. Plots showing the roundness and sphericity data in isolation are shown in Fig. 6, confirming that all five sands are predominantly sub-rounded to sub-angular in roundness and spherical. All four candidate sands have broadly similar geometrical ranges to the Chertsey sand. However, the percentage of discoidal particles (flat and rounded particles in shape) is relatively higher in the Poyle sand, suggesting that it could be eliminated as being the least suitable. Further factors to consider include:

- The limited availability of the Eton sand supplies,
- The Chertsey and Stanwell quarries are sited in different terraces to the original Ham River Sand source, while the Shepperton pit is from the same terrace (and therefore age) as the original HRS.

On the basis of the above arguments, the Shepperton sand appeared to be the most promising candidate, and the mechanical properties studies concentrated on samples from this location.

Table 2 shows the specific gravities of the sands subjected to detailed testing, while the maximum and minimum void ratios found by a range of testers and test procedures are summarised in Table 3. These data are plotted with measurements made according to the current BS1377-4:1990 or with similar methods in earlier HRS studies in Fig. 7. For reference the median void ratios (at relative density of 50%) are plotted in the figure though the median void ratio is not an intrinsic parameter but a test dependent quantity for sand (Barton & Palmer 1989, Cubrinovski & Ishihara 2002). In most cases determinations of the maximum and minimum void ratios have been determined according to BS1377-4:1990 or equivalent. The minimum void ratio measurements made by Kolbuszewski (1948) and Daramola (1979) involved a larger compaction effort than BS1377-4:1990 and differences in the compaction method might alter the degree of particle crushing and hence the minimum void ratio. However, comparisons among the test results for the original HRS (including reused samples) indicate that, over the range applied, the degree of compactive effort did not affect the minimum void ratio greatly. Substantial differences were seen between the maximum and minimum void ratios of the reused original HRS and the Chertsey sand when the same testing methods are applied. Variations in material behaviour appear to be the main reason for divergence in the void ratio limits, rather than changes in test method details.

Although the median void ratios fall within a relatively narrow range (0.69-0.72), the differences ($e_{max} - e_{min}$) reported between 1969 and 1988 for the maximum and minimum void ratios of HRS are far larger (at around 0.45) than those noted in 1948 for the original samples (around 0.35) and for the Shepperton and Chertsey sands (around 0.28 and 0.30 respectively). The spread of values is not ideal and it is clearly important to mix the samples obtained from the finally selected replacement source to achieve a single large homogenous stock for future research work.

Mechanical properties comparison

The mechanical properties of the graded Shepperton sand were assessed by means of: (i) drained direct shear box tests, (ii) one-dimensional compression tests to high loads and (iii) undrained stress-path triaxial tests incorporating multiple bender element shear wave velocity measurements. These data were compared with measurements for the original Ham and Chertsey sands using both new and pre-existing data. The initial void ratio of the test specimens was selected as the most suitable single index to aim for in aligning test conditions to provide meaningful comparisons. Efforts were made in all the new testing to form samples with similar initial void ratios to the existing data sets.

Direct shear box tests

The direct shear box samples were rectangular prisms 60mm long, 60mm wide. Specimens were prepared by pouring 130g of air-dried sand into the box through a funnel. A minimal free fall height was adopted to obtain loose samples, while dense samples were achieved by tapping the box after pouring to reduce the sample height from 23.5mm (loose) to 21mm (dense). Tests were conducted after compression to vertical stresses of 51.4, 200, & 386kPa, with the upper half of the box being lifted by 0.5mm before shearing. Imposing this gap increased the average vertical stress acting on the soil at the middle of the box by 4.3kPa, because the self-weight of the upper half box was then carried through the soil, giving average normal stresses of 55.7, 205 & 391kPa, respectively. The samples were then sheared at a displacement rate of 0.6mm/min.

Figure 8 compares the conventional angles of shearing resistance $\phi' = \tan^{-1}(\tau/\sigma'_v)$ at peak and ultimate state for the Shepperton, Chertsey and original Ham River sands, taking the latter data from Kuwano (1999) and Hafiz (1950). It should be noted here that Hafiz's tests on the Ham sand were undertaken in a very large shear box (sample size: 0.305×0.305×0.152m) and testing method may have been different from the standard direct shear box tests. No strong stress level dependency is evident, although the peak and ultimate angles of shearing resistance of the dense Chertsey sand at the lower stress level are slightly different from the higher stress level results. Table 4 summarises the angles of shearing resistance in the range of σ'_{v0} =50-400kPa. All the sands show practically the same results although the peak angles of the Shepperton sand may be up to one degree higher than those for Chertsey and the reverse may be true for the ultimate angles states.

Compression tests

The compressibilities of the graded Chertsey, Shepperton and Stanwell sands were examined by oedometer tests on 38mm diameter samples. Normal stresses up to 36MPa were applied following a staged maintained-load procedure that involved eight loading and five unloading stages. Loose samples were formed by pluviation through water and the maintained-load stages were ended, and each new load applied, when the residual volumetric strain creep rate had reduced below 0.1%/day. Medium term creep straining was very significant at the higher stress levels. The data are plotted in Fig. 9, in terms of specific volume ($v = 1 + e$) and σ'_v, together with the Normal Compression Line (NCL) for the HRS used during the late 1980s, as reported by Coop & Lee (1993). As is typical for sands, the initial portions of the first time loading curves appear as relatively flat curves that gradually rotate towards the NCL, joining this line at stresses that depend on their initial void ratio and crushing characteristics. In this case the samples conformed to Coop and Lee's NCL when $\sigma'_v > 15$MPa. Kuwano (1999) and Jardine *et al*. (2001) show that the HRS undergoes considerable creep and predominantly plastic straining from the earliest stages in such tests, while Skinner (1975) and Coop and Lee (1993) have shown that particle crushing dominates as the sand state approaches the NCL. The high-pressure compressibilities of the four reconstituted sands are closely comparable, even though they come from different terraces. Their NCLs are controlled by the particles' mineral constituents, roundness and shape, and size distributions. The initial fabrics and void ratios affect behaviour strongly at lower stress levels.

Undrained Triaxial Tests

Triaxial tests were undertaken in a standard hydraulic stress path cell (Bishop & Wesley 1975). Specimens with 38mm diameter and 76mm height were prepared from air-dried sand. The sand was de-aired in distilled water in a vacuum chamber and then transferred gently by spoon into a de-aired water filled latex membrane retained by a stretcher mould. After gentle levelling and sealing with a top cap, a suction of 20kPa was applied and the mould removed. The sample dimensions were then measured and local strain instrumentation attached. The samples were then compressed, isotropically or anisotropically, to a mean effective stress of $p'_0 = 400$kPa, while maintaining a backpressure of 350kPa. After allowing a suitable period for creep straining (about two days), undrained compression or extension tests were performed to failure at an axial strain rate of 1% per hour. In all the cases, a rubber suction cap was used to connect the top cap to the internal deviator load cell once the saturation stage was completed. All the test conditions are tabulated in Table 5 together with the summary of the test results, along with the details of comparator tests by Reades (1972), Ovando-Shelly (1986) and Kuwano (1999). It should be noted that:

- The relative void ratios applying before shearing are marginally different (0.78 [Dr≈25%] for the original HRSs, 0.75 [Dr≈30%] for the Chertsey, and 0.72 [Dr≈40%] for the Shepperton samples),
- The water pluviation methods are different (the sand was poured through a funnel for the reused original

HRS and the Chertsey, while being immersed by gentle spooning for the original HRS and the Shepperton samples),

- The *K* (where $K = \sigma'_3 / \sigma'_1$) values adopted for anisotropic consolidation were slightly different (0.55 for the original HRSs, and 0.5 for the Chertsey and Shepperton sands), and
- The loading rates are different (an axial strain rate of 6%/hr for the original HRSs, 0.8%/hr for the Chertsey, and 1%/hr for the Shepperton).

Multiple Bender element tests (Shirley & Hampton 1978, Viggiani & Atkinson 1995) were undertaken in two of the triaxial tests (Shepperton sand Test codes 17 & 18). Bender elements were installed in the top cap and pedestal to measure the vertical shear wave velocity of V_{vh} and tests were performed at $p' =$50, 100, 200 & 400kPa. In each set of measurements eight single sinusoidal waves with frequency f = 4 to 11kHz were input. The following parameters were interpreted for each stage (i) the frequency response function $H(f)$, (ii) the unit-impulse response function $h(t)$, and (iii) the cross-correlation function $R_{12}(t)$ by manipulation of the input and output signal records ($x_1(t)$ & $x_2(t)$, respectively) as described by Bendat & Piersol (1993). The first arrival time of a received signal can be calculated from either (i) the phase shift of $H(f)$, or (ii) the times associated with the peaks of the $h(t)$ and $R_{12}(t)$ functions. Once the arrival times are known the shear wave velocity may be calculated from the tip-to-tip travel distance and the relevant vertical shear stiffness can assessed as $G_{vh} = \rho V_{vh}^2$.

The variations in G_{vh} with p' during compression are plotted in Fig. 10, together with Kuwano's corresponding experiments on the Chertsey sand; all G_{vh} values are normalised by the void ratio function $F(e) = (2.17 - e)^2 / (1 + e)$. The curves show that (i) at stress levels above 150 kPa the Shepperton results are not sensitive to the method of Bender Element test interpretation and (ii) the shear modulus characteristics of the Shepperton and Chertsey sands are closely comparable.

Figure 11 presents the undrained effective stress paths for normally isotropically consolidated sand samples and the same plots normalised by the mean effective stress at q=0 are shown in Fig.12, while Fig. 13 shows the corresponding plots for the anisotropically consolidated samples. Since the samples for compression and extension tests on the original HRS (Tests 2 & 4) were consolidated with the higher confining pressure, these are not plotted in Fig.11, while they appear in the normalised plot in Fig.12 for comparison even though the compression test on the original HRS (Test 2) was not isotropically consolidated but was anisotropically consolidated with K=1.2. While the tests show broadly comparable trends, there are some differences in the detailed behaviour. The Shepperton sand showed an unusually contractant response in Test 17 (compression with $e_0 =$ 0.78) before reaching its phase transformation point, while Test 11 (extension with $e_0 = 0.72$) had a less contractant response than the other samples. These features may reflect differences in initial void ratios and the possible disturbance of the Test 11 sample. The Test 11 sample is considered less reliable as some minor disturbance was experienced when the sample top cap was connected to the load cell through the suction cap arrangement. Normalisation of the plots by their mean effective stresses at q=0 makes the effect of difference in initial void ratio on the stress path response clear as seen in Fig.12: The larger the initial void ratio the more contractive the stress path response, although not all the paths lie in this order. It is interesting to note that the effective stress paths of the isotropically consolidated samples diverge more significantly than those of the anisotropically consolidated specimens. It is likely that the isotropically consolidated samples are more susceptible to variations in the sample's initial fabric and detailed setting up procedure. Anisotropic compression is more likely to iron out any initial imperfections in sample alignment and reduce differences in initial fabric. Although some differences can be seen in the soil responses due to the reasons discussed above, the overall undrained responses of the Shepperton sands are broadly comparable to those of the original HRS and Chertsey sands.

Conclusions

Supplies are exhausted of both the Ham River Sand (HRS) and the 'new HRS' replacement sand from Chertsey that have been used at Imperial College for many years. A study of four candidate replacement test sands has been completed that sought a local mid-Thames alluvial terrace material with comparable mechanical properties. The study considered geological and practical factors as well as microscopic visual comparisons and direct shear box, high-pressure oedometer, bender element and undrained triaxal tests. The main conclusions are:

- The mid-Thames terrace materials have a wide range of particle sizes and have to be graded and mixed to produce standard test sands. All material retained by the 600μm sieve has been rejected as being unsuitable.
- The samples found from all sites (after passing the 600μm sieve) had similar constitutent particles (minerals, roundness and sphericity) to the HRS, even though they came from more than one Thames terrace. The Shepperton sand provided the best overall match in terms of particle characteristics and geological origin.
- The shear strength parameters obtained from direct shear box tests on the Shepperton sand are very close to those for the Chertsey sand and original HRS.
- High-pressure compression oedometer tests on the Shepperton, Stanwell, Chertsey and HRS samples all gave similar results. The samples' NCLs depend on their mineral constituents, particle distributions, particle shapes and roundness.
- Bender Element tests indicate a close correspondence between the shear stiffness behaviour of the Shepperton and Chertsey deposits.
- The overall undrained triaxial test response of the Shepperton sand is comparable with, if not identical to those of the reused original HRS and Chertsey sand. Some of the differences seen in the undrained responses may be due to sample density variations.
- Overall, graded samples of the Shepperton sand may provide a suitable substitute for the exhausted HRS stocks. However, some slight differences in behaviour may be expected. It is also noted that re-used samples that may have had their macro or micro-structures altered by prior testing may have different characteristics to samples that have not been pre-failed. Even sieving and washing processes are likely to modify the sands' characteristics to some extent.

Acknowledgements

The first Author was supported in his stay at Imperial College by a Platform Grant funded by the UK Engineering and Physical Sciences Research Council (EPSRC). The contributions of current and former colleagues at Imperial College are also acknowledged gratefully.

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Table 1—Terraces and locations

Terrace	Gravel name	Location
1st	Shepperton	*Chertsey* **Eton** **Poyle**
2nd	Kempton Park	*Ham* **Shepperton**
3rd	Taplow	**Stanwell**

(*Italic* for previously used sites and **Bold** for new sites.)

Table 2—Specific gravities

Location name	Examined by	
Shepperton	(This study)	2.67
Stanwell	(This study)	2.66
Chertsey	Walker (1991)	2.67
	Porovic (1995) & Kuwano (1999)	2.66
Ham	Kolbuszewski (1948), Hafiz (1950) & Skinner (1975)	2.70
	Reades (1972) & Daramola (1979)	2.68
	Green (1969, Batch 1)	2.67
	Green (1969, Batch 2), Shibuya (1985), Ovando-Shelly (1986) & Georgiannou (1988)	2.66

Table 3—Maximum and minimum void ratios

	Shepperton	Chertsey	Reused Ham	Ham	
Maximum void ratio	0.83*1	0.82-0.85*1	0.90*1	0.92-0.94*1	0.81*1
Minimum void ratio	0.549*2	0.539-0.547*2	0.450-0.465*2	0.456*3	0.462*4

*1: BS1377-4:1990 or equivalent (Determination method essentially has not been changed since 1940s.)
*2: BS1377-4:1990 or equivalent (Each layer is compacted with a vibrating hammer for 2 min. 3 layers for 1L mould.)
*3: Daramola (1979) (Each layer is compacted with a vibrating hammer for 2 min. 4 layers for 0.8L mould.)
*4: Kolbuszewski (1948) (At 15 min. the duration of compaction is much longer than the BS1377 test.)

Table 4—Angles of shearing resistance in direct shear box tests (in deg., σ'_{v0} =50–400kPa)

	Dense sand			Loose sand	
	e_{ini} [Dr (%)]	Peak	Ultimate	e_{ini} [Dr (%)]	Ultimate
Shepperton	0.57 [93]	38.7	30.0	0.74 [32]	30.3
Chertsey*1	0.56 [96]	37.8	31.2	0.79 [20]	30.9
Ham*2	0.60 […]	40	…	0.82 […]	32

*1: Kuwano (1999), & *2: Hafiz (1950) with 1ft^2-area shear box under σ'_{v0} =50–200kPa

Table 5—Summary of triaxial tests

	Test code	e_{ini} [Dr (%)]	e_0 [Dr (%)]	p'_0 (kPa)	K	Shear mode	$\dot{\varepsilon}_a$ (%/hr)	p'_{PTP}/p'_0	ϕ'_{PTP} (deg.)	ϕ'_{max} (deg.)
Shepperton	15	0.72 [41]	0.70 [47]	400	1	$+\Delta\varepsilon_a$	1	0.80	26.9	32.3
	17	0.80 [11]	0.78 [19]	400	1	$+\Delta\varepsilon_a$	1	0.60	27.3	32.7
	11*1	0.75 [28]	0.72 [38]	400	1	$-\Delta\varepsilon_a$	1	0.42	25.0	25.8
	18	0.73 [35]	0.71 [45]	400	0.5	$+\Delta\varepsilon_a$	1	0.86	28.5	33.5
	13	0.73 [34]	0.72 [40]	400	0.5	$-\Delta\varepsilon_a$	1	0.20	23.6	25.6
Chertsey*2	h11	0.77 [26]	0.75 [33]	400	1	$+\Delta\varepsilon_a$	0.8	0.74	29.0	32.6
	h12	0.78 [23]	0.75 [31]	400	1	$-\Delta\varepsilon_a$	0.8	0.14	27.7	29.7
	h21	0.77 [27]	0.75 [34]	400	0.5	$+\Delta\varepsilon_a$	0.8	0.85	29.7	32.4
	h24	0.78 [24]	0.76 [29]	400	0.5	$-\Delta\varepsilon_a$	0.8	0.14	28.2	29.4
Reused original HRS*3	58	0.81 [21]	0.79 [25]	410	1	$+\Delta\varepsilon_a$	6	0.62	30.1	33.5
	76	0.79 [24]	0.77 [30]	400	1	$-\Delta\varepsilon_a$	6	0.18	24.2	26.5
	64	0.80 [23]	0.78 [28]	410	0.55	$+\Delta\varepsilon_a$	6	0.78	29.5	32.5
	89	0.82 [19]	0.80 [23]	400	0.55	$-\Delta\varepsilon_a$	6	0.16	21.3	28.6
Original HRS*4	2	0.83 [20]	0.78 [30]	646	1.2	$+\Delta\varepsilon_a$	6 (?)	0.45	30.3	33.3
	4	0.84 [18]	0.79 [28]	685	1	$-\Delta\varepsilon_a$	6 (?)	0.06	25.3	27.9
	3	0.83 [21]	0.79 [28]	434	0.55	$-\Delta\varepsilon_a$	6 (?)	0.04	25.4	27.9

*1: Small disturbance was imposed to the sample when connected to the load cell through the suction cap.
*2: Kuwano (1999), *3: Ovando-Shelly (1986), & *4: Reades (1972)

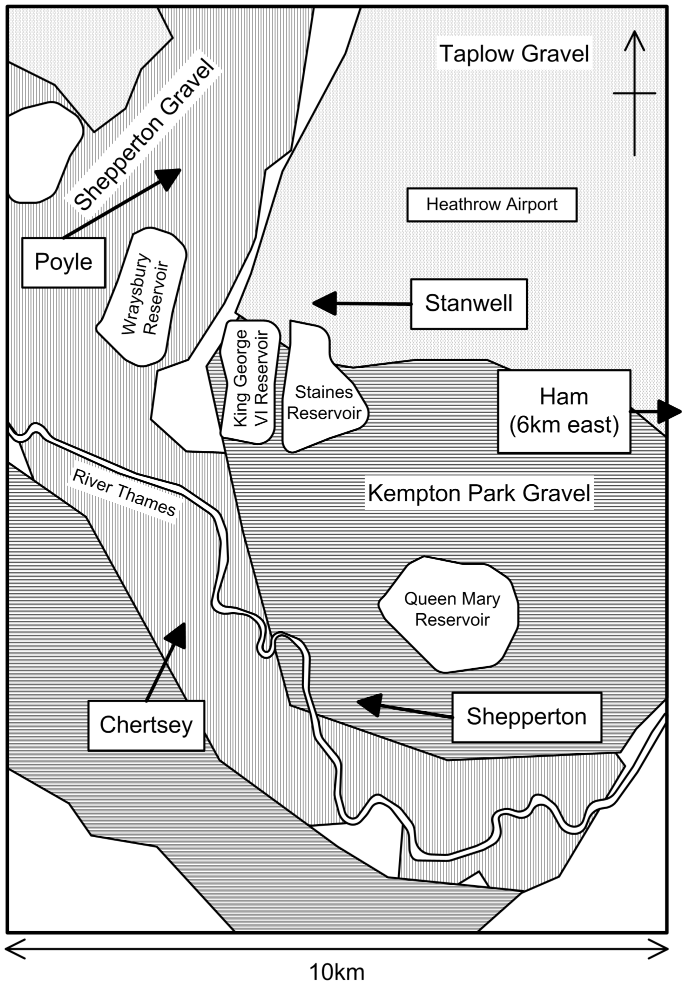

Fig. 1: Distributions of the river terrace deposits of the post-diversionary River Thames and its tributaries with location of quarries

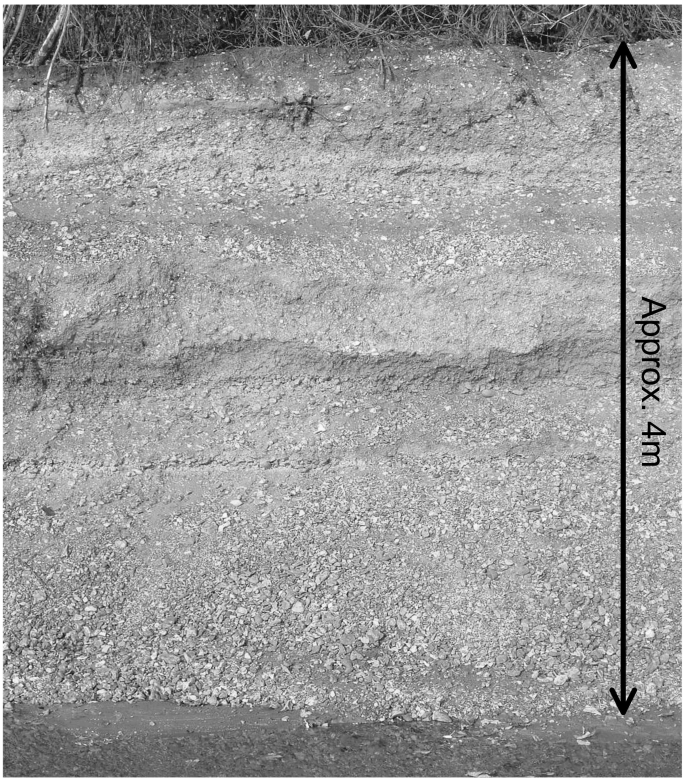

Fig. 2: Exposed slope at Stanwell Quarry

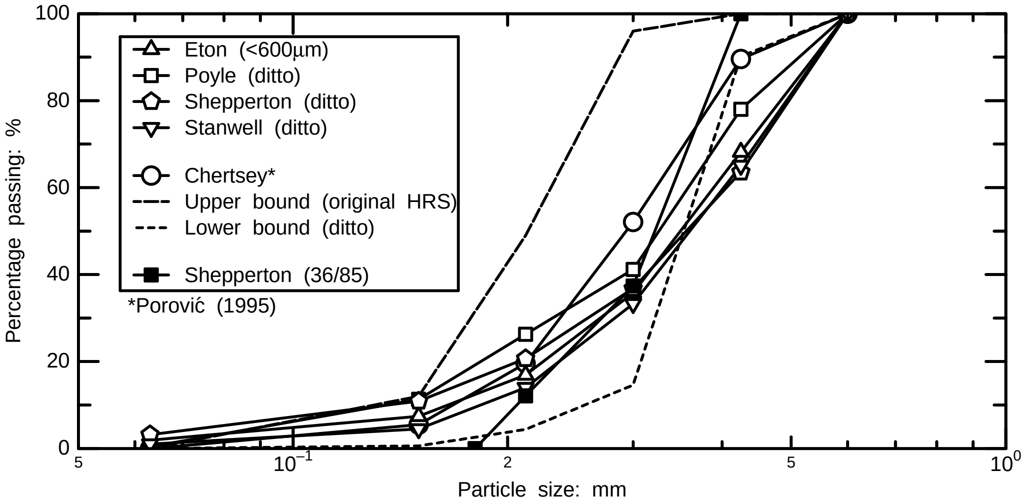

Fig. 3: Particle size distributions

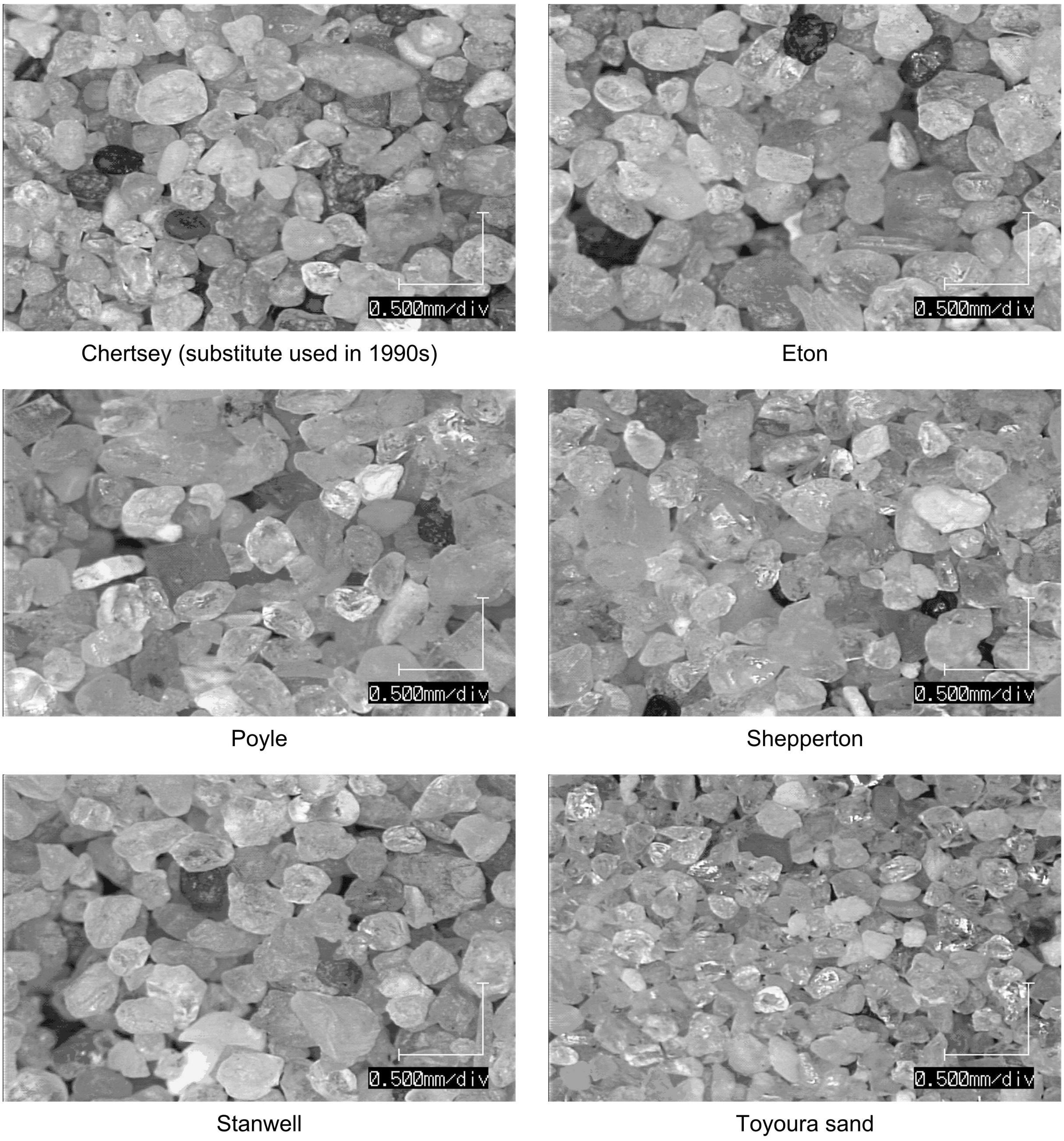

Fig. 4: Microscopic photos of particles

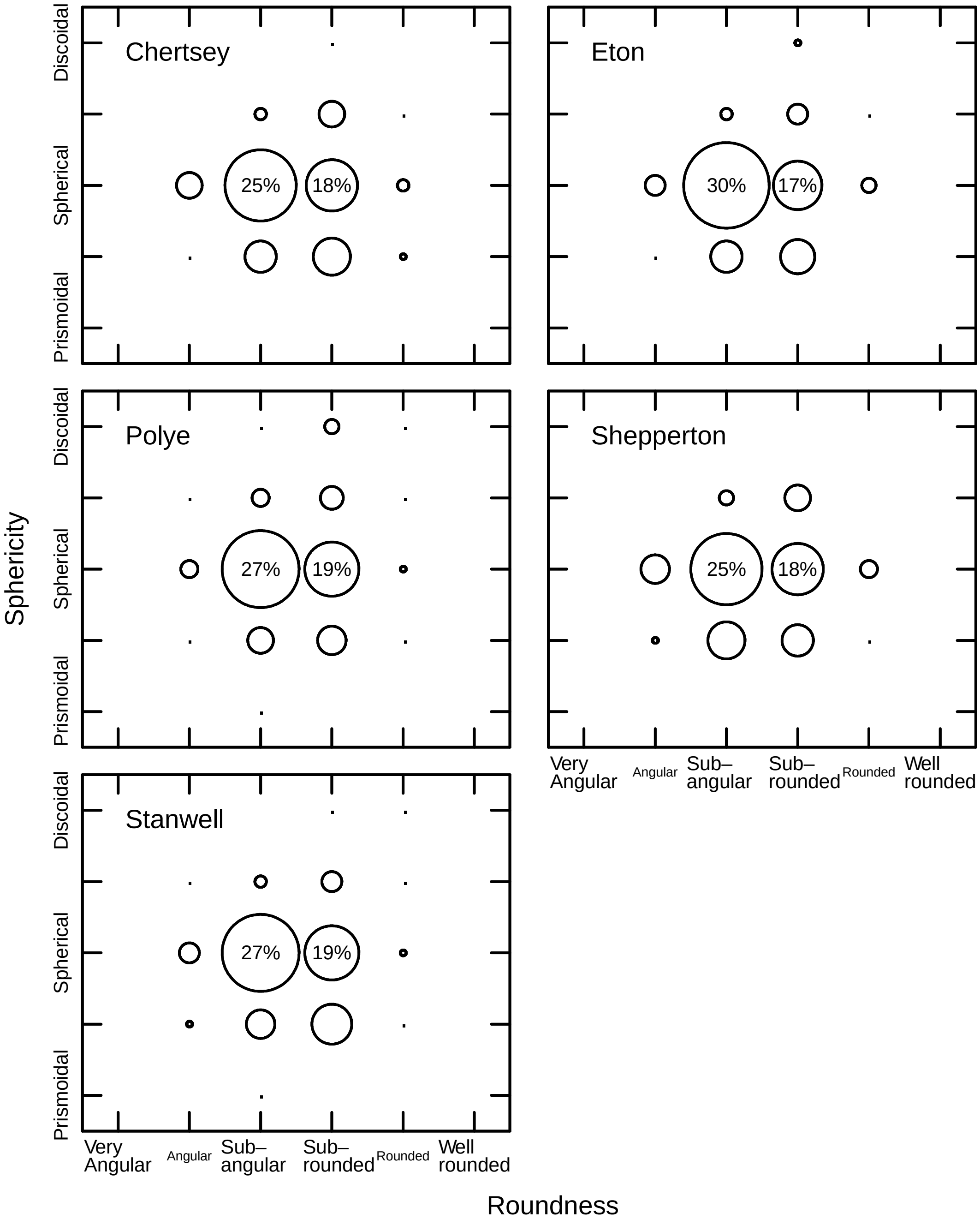

Fig. 5: Bubble charts of frequency percentage in visual comparison of roundness and sphericity

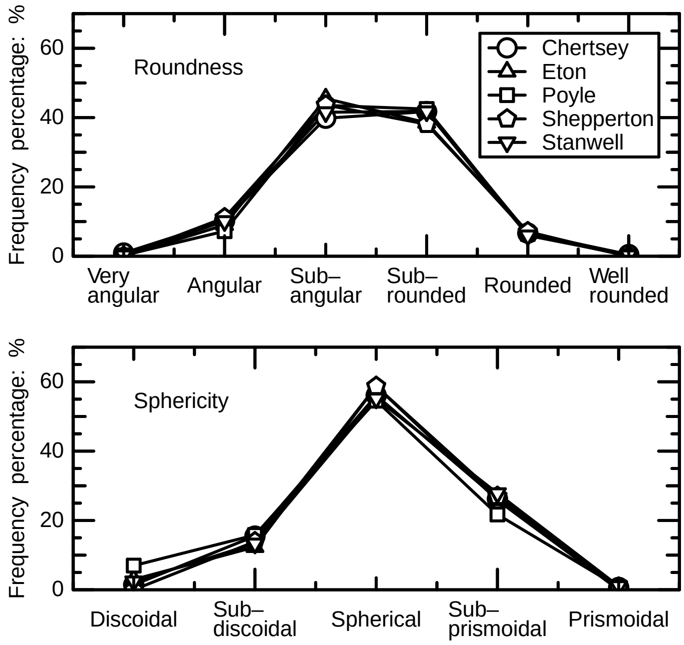

Fig. 6: Frequency percentage in visual comparisons of roundness and sphericity

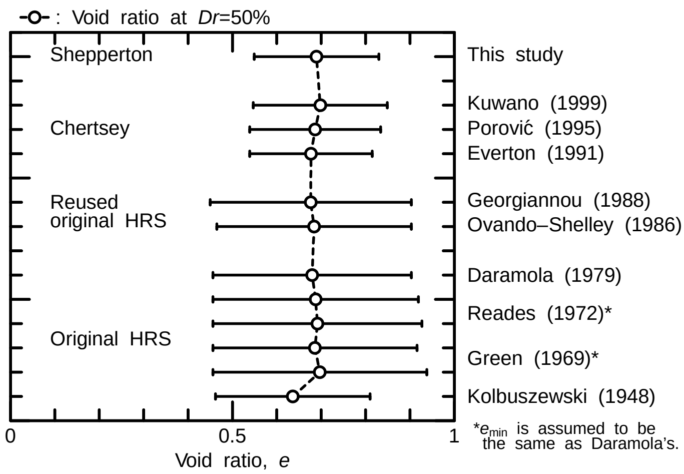

Fig. 7: Maximum and minimum void ratios

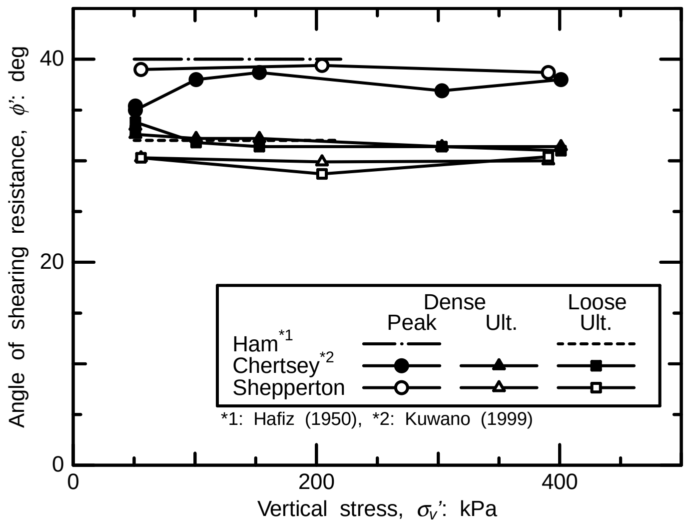

Fig. 8: Angles of shearing resistance in direct shear box test

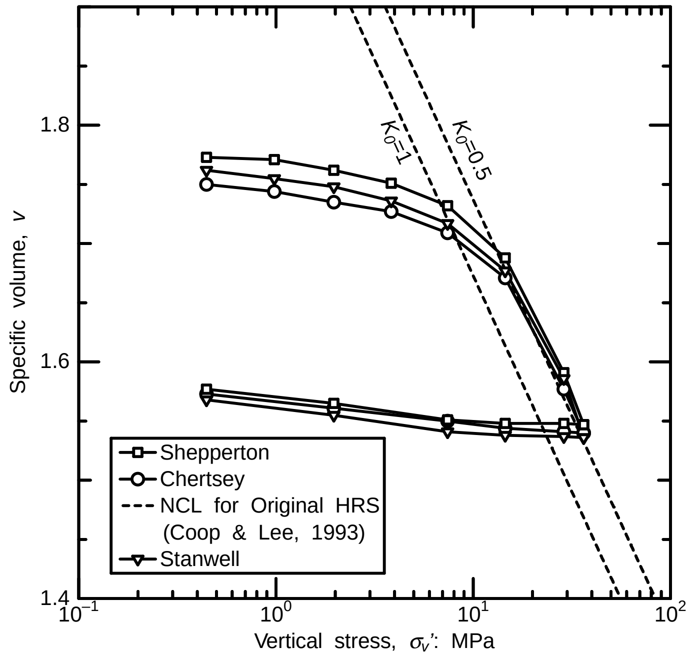

Fig. 9: Specific volume changes in one dimensional compression and swelling

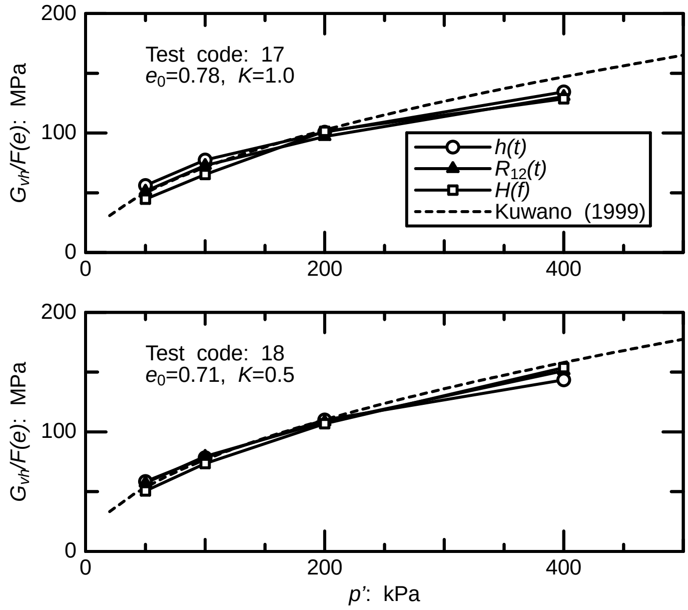

Fig. 10: Comparisons of shear modulus during consolidation

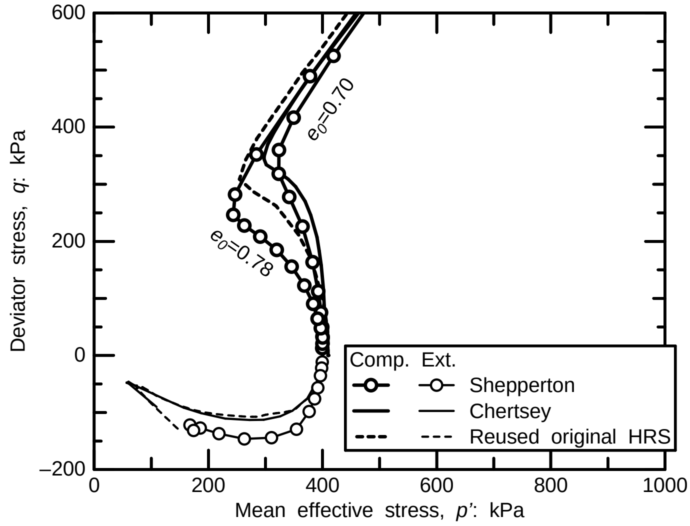

Fig. 11: Effective stress paths for undrained triaxial tests on isotropically consolidated sands

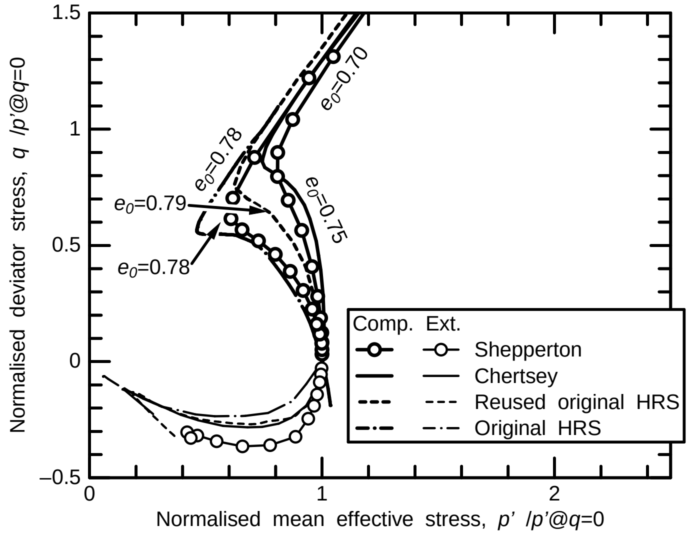

Fig. 12: Normalised effective stress paths for undrained triaxial tests on isotropically consolidated sands

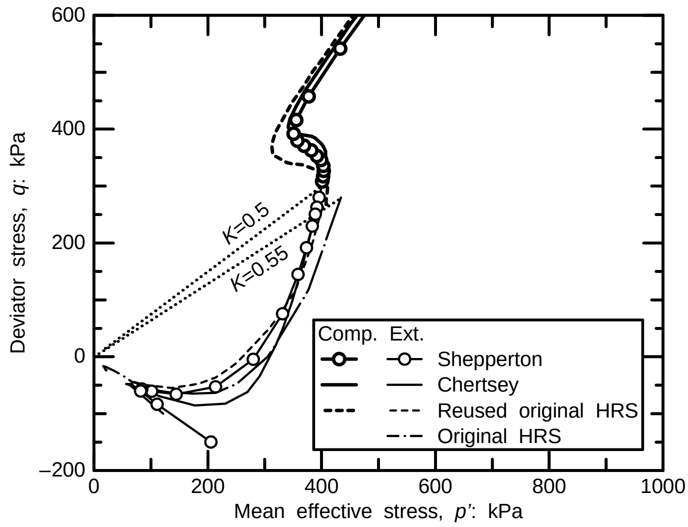

Fig. 13: Stress paths for anisotropically consolidated sands