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Determining G-γ decay curves in sand from a Seismic Dilatometer Test (SDMT)

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ABSTRACT: This paper investigates the use of the Seismic Dilatometer Test (SDMT) for the determination of in situ decay curves of sand stiffness with strain level (G-γ curves or similar). In situ, laboratory and field data (including footing and self-boring pressuremeter tests) obtained at a silica sand site and a calcareous sand site in Western Australia are used for this investigation. The approach adopted relies on the ability of SDMT to provide a small strain modulus (G_0 from Vs), a "working strain" modulus (G_{DMT} from M_{DMT}) and an "operational strain" modulus (G_{DV} from M_{DV}). Thus, in situ G-γ decay curves are tentatively constructed by fitting curves through these three points. The approach is based on the premise that M_{DMT} is a reasonable estimate of the working strain modulus (e.g. Monaco et al. 2006 and Marchetti et al. 2008), while M_{DV} is a modulus operating at the settlement ratio s/B of 1.8%, applied by the flat dilatometer, derived using Lehane & Fahey (2004). The paper illustrates the potential of using the SDMT to obtain in situ G-γ decay curves, but also indicates that additional research is required to improve the reliability of the proposed approach.

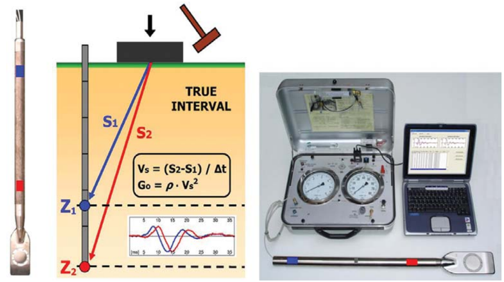
1 INTRODUCTION

The non-linear stress-strain behaviour of soil can be estimated from in-situ and laboratory tests. As described by Ishihara (2001), several in-situ test methods are employed to determine the maximum shear modulus G_0 (from the shear wave velocity, V_s): Down-Hole (DH) and Cross-Hole (CH) seismic methods, Seismic Dilatometer Test (SDMT) and Seismic Cone Penetration Tests (SCPT), Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW). The Dilatometer test (DMT), Pressuremeter test and Plate Loading test are also performed to allow assessment of the stiffness of soils at moderate and large strains. The Cone Penetration Test (CPT) end resistance (q_c) and the Standard Penetration Test (SPT) blow count (N) reflect the strength of the in-situ soil and therefore correlations between these parameters and stiffness are approximate, at best.

The maximum shear modulus G_0 and the shear stiffness-shear strain (G-γ) degradation curve can be determined using a variety of laboratory testing procedures. However such tests are sophisticated and expensive, and also rely on the retrieval of good quality samples. It is therefore of interest to investigate if in-situ tests can be used to measure G-γ curves. This paper considers the seismic dilatometer test (SDMT) as a possibility where the G-γ curve is derived from (i) the "initial elastic modulus" G_0 from the shear wave velocity V_S, (ii) a "working strain modulus" (G_{DMT}) corresponding to the Marchetti (1980) constrained modulus M_{DMT}, and (iii) an "operational strain modulus" (G_{DV}) related to the in-situ stiffness at a settlement ratio (s/B) of 1.8%. This hypothesis will be examined considering the Shenton Park (silica sand) and Ledge Point (calcareous sand) sites in West Australia, where in-situ, laboratory and field tests were performed.

2 THE SEISMIC DILATOMETER (SDMT)

The seismic dilatometer (SDMT) is the combination of the mechanical flat dilatometer (DMT), introduced by Marchetti (1980), with a seismic module for measuring the shear wave velocity V_S. From V_S the small strain shear modulus G_0 may be determined using the theory of elasticity. The test is conceptually similar to the seismic cone (SCPT). First introduced by Hepton (1988), the SDMT was subsequently improved at Georgia Tech, Atlanta, USA (Martin & Mayne 1997, 1998; Mayne et al. 1999).



(a) (b) (c)

Figure 1. Seismic dilatometer test (Marchetti et al. 2008): DMT blade and seismic module (a); schematic test layout (b); seismic dilatometer equipment (c).

A new SDMT system has been recently developed in Italy. The seismic module (Fig. 1a) is a cylindrical element placed above the DMT blade, provided with two receivers spaced 0.5 m apart. The signal is amplified and digitized at depth. The true-interval test configuration with two receivers avoids possible inaccuracy in the determination of the "zero time" at the hammer impact, sometimes observed in the pseudo-interval one-receiver configuration. Moreover, the couple of seismograms recorded by the two receivers at a given test depth corresponds to the same hammer blow and not to different blows in sequence, which are not necessarily identical. Hence the repeatability of V_S measurements is considerably improved.

V_S is obtained (Fig. 1b) as the ratio between the delay of the arrival of the impulse from the first to the second receiver (Δt) and the difference in distance between the source and the two receivers ($S_2 - S_1$). V_S measurements are obtained every 0.5 m of depth (while the mechanical DMT readings are taken every 0.20 m). The shear wave source at the surface is an automatic hammer or a pendulum hammer (≈ 10 kg) which hits horizontally a steel rectangular beam pressed vertically against the soil (by the weight of the truck) and oriented with its long axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the generated shear wave.

The determination of the delay from SDMT seismograms, normally obtained using a cross-correlation algorithm rather than relying on the first arrival time or specific single points in the seismogram, is generally well conditioned. It may be noted the repeatability of the V_S profile is very high, similar to the repeatability of the other DMT parameters, if not better. The coefficient of variation of V_S is in the range 1–2%.

Validations of V_S measurements by SDMT via comparison with V_S measurements obtained by other in situ seismic tests at various research sites are reported by Marchetti et al. (2008).

3 IN SITU G-γ DECAY CURVES IN SAND

3.1 *Seismic Dilatometer (SDMT)*

The approach adopted relies on the ability of SDMT to provide routinely in sand at each depth both a small strain modulus (G_0 from V_S), a "working strain" modulus (G_{DMT} from M_{DMT}) and an "operational strain" modulus (G_{DV} from M_{DV}). These three points could be tentatively used to fit in situ decay curves.

3.1.1 G_{DMT} *("working strain modulus")*

As a first approximation, the working strain modulus G_{DMT} can be derived from the constrained modulus M_{DMT}, obtained from the flat dilatometer DMT (TC16, 2001) using the linear elastic formula (Eqn. 1):

$$G_{DMT} = \frac{M_{DMT}}{2(1-\nu)/(1-2\nu)} \tag{1}$$

where ν = Poisson's ratio (taken equal to 0.2 in sand).

The assumption that M_{DMT} can provide a reasonable estimate of the operative working strain modulus is supported, for example, by research of Monaco et al. (2006), who reviewed numerous well documented case histories. Monaco et al. found that the average ratio of settlements predicted using M_{DMT} was ≈ 1.3 the observed settlement, with most predictions lying within 50% of the actual settlements. Marchetti et al. (2008) also show how the use of M_{DMT} predicted reasonable settlements at the test site of Treporti, Venice, Italy.

It is necessary to know the elemental shear strain that the value of G_{DMT} corresponds to (referred to here as γ_{DMT}). Mayne (2001) indicates a range $\gamma_{DMT} \approx$ 0.05–0.1%, while Ishihara (2001) suggests that the range can be much higher, varying from 0.01% to 1%.

Marchetti et al. (2006) re-constructed soil stiffness decay curves for the Treporti case history from local vertical strains measured at the center of the embankment under each load increment. The intersection of the DMT data points with the observed in-situ decay curves indicated that γ_{DMT} was in the range 0.01–0.1% in sand and between 0.1% and 1% in silt. More recently, Amoroso (2011) examined data from many tests sites and concluded that γ_{DMT} varied from 0.01% to 0.15% in sand, 0.1% to 0.2% in silt/clay and to in excess of 2% in soft clay.

3.1.2 G_{DV} *("operational strain modulus")*

Lehane & Fahey (2004) investigated the influence of installation disturbance on the DMT modulus and subsequently employed a database of SCPTs and DMTs at a range of sand sites to propose the following approximate expression (Eq. 2) for the operational modulus M_{DV} of a rigid footing at a settlement s to width B ratio s/B of 1.8% (note that $s = 1.1$ mm is the movement at the DMT membrane centre; $B = 60$ mm is the diameter of the DMT membrane):

$$M_{DV} = 1.3E_D/\sqrt{K_D}; \quad s/B = 1.8\% \tag{2}$$

where E_D = dilatometer modulus; K_D = horizontal stress index; E_D, K_D are DMT parameters derived directly from the lift-off pressure and pressure at a membrane expansion of 1.1 mm (TC16, 2001).

Eq. 2 ignores differences between creep rates operational in a DMT and beneath a footing as well as the potential presence of inherent anisotropy in the in situ deposit. Corrections for creep factor f_{creep} and for anisotropy factor f_{aniso} lead to the revised relationship (Eq. 3):

$$M_{DV} = 1.3f_{\text{creep}}f_{\text{aniso}}E_D/\sqrt{K_D}; \quad s/B = 1.8\% \tag{3}$$

The results, illustrated in the following paragraphs, take the creep factor f_{creep} equal to 1, assuming creep differences between the DMT and footing tests can be ignored, and the anisotropy factor f_{aniso} equal to 1, considering that Equation. 2 has been obtained from 15 sand sites in Perth region.

The corresponding shear modulus, G_{DV}, can be derived from M_{DV} using linear elasticity as:

$$G_{DV} = \frac{M_{DV}}{2(1-\nu)/(1-2\nu)} \tag{4}$$

where ν = Poisson's ratio (taken equal to 0.2 in sand).

This "operational modulus" was included in the formulation proposed by Lehane & Fahey (2004) to predict the load-displacement response of 4 test footings at a sand site in Perth (Western Australia). Good agreement was observed, although Lehane & Fahey (2004) also show that the same approach over-predicted the load-displacement response in another series of footing tests conducted in Texas. This over-prediction was attributed to effects of over-consolidation at the Texas site which had not been allowed for in the initial set of predictions.

3.2 *Self-Boring Pressuremeter Test (SBPT)*

The self-boring pressuremeter test (SBPT) is well conditioned for determining soil parameters. However, the mode of deformation is such that the strain imparted to soil elements reduce from a maximum at the cavity (ε_c) to zero at a large distance from the device i.e. it is not an element test. In place of conducting a Finite Element back-analysis of a SBPT to derive elemental parameters, Jardine (1992) proposed a 'transformed strain approach' to estimate an elemental G_s–ε_s curve from a G_p–ε_c curve, where G_s is the secant shear stiffness at a (triaxial) shear strain of ε_s; G_p = pressuremeter shear stiffness, ε_c = cavity strain. Jardine (1992) suggested that G_p–ε_c curves may be transformed into G_s–ε_s characteristics by simply dividing each ε_c data point by the right-hand side of the following expression:

$$\frac{\varepsilon_c}{\varepsilon_s} = 1.2 + 0.8Log\frac{\varepsilon_c}{10^{-5}}, \quad \text{for} \quad G_P = G_s \tag{5}$$

The engineering shear strain (γ) is 3/2 times the triaxial shear strain (ε_s).

4 WEST AUSTRALIA SAND TEST SITES

The following paragraphs present the results of tests carried out at two different test sites in Western Australia (Shenton Park, a silica sand site, and Ledge Point, a calcareous sand site). A range is proposed for the shear strains γ_{DMT} (corresponding to the working strain modulus G_{DMT}) and γ_{DV} (corresponding to the operational strain modulus G_{DV}), by the comparison of results of seismic dilatometer tests (SDMTs) and flat dilatometer tests (DMTs), seismic cone penetration tests (SCPTs), self-boring pressumeter tests (SBPTs) and laboratory tests. Full details are available in Amoroso (2011).

4.1 *Shenton Park*

The Shenton Park test site is located in the western suburbs of Perth. The site comprises up to 5–10 m of the Spearwood Dune Sand overlying the Tamala Limestone caprock (Fahey et al. 2007). Strength and stiffness parameters have been evaluated using CPTs, SCPTs, DMTs, SDMTs, SBPs, boreholes (BH), laboratory tests and footing tests (F), carried out between 2003–2007 (Lehane et al. 2004, 2009, Schneider et al. 2008) and 2008–2010 (Amoroso 2011). Laboratory tests consisted of triaxial tests with local strain measurements and bender element tests a performed on reconstituted specimens.

The research presented here focuses on the data obtained during geotechnical campaign of 2006–2007, as shown in Figure 2. The sand is quite homogeneous within the upper 4.5 m, as shown by DMTs (Fig. 3) and SCPTs (Fig. 4).

The SBPs have been carried out in the boreholes in the upper 5 m and for each test three unload-reload (U-R) loops were typically performed. Table 1 summarizes SBP data:

- z = depth;
- s = slope of the expansion curve;
- ϕ' = friction angle;
- ψ = dilatancy angle;
- G_{ur} = unload-reload shear modulus;

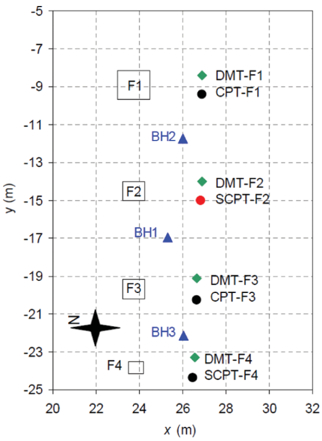


Figure 2. Shenton Park test site in 2006–2007 (Schneider et al. 2008).

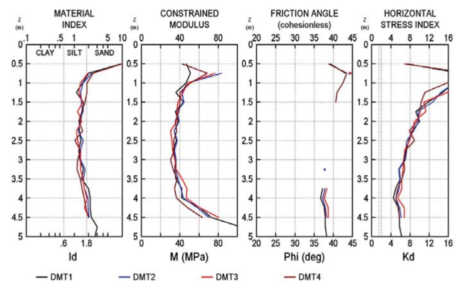


Figure 3. DMT results at Shenton Park: Material index I_D, constrained modulus M_{DMT}, friction angle ϕ', horizontal stress index K_D.

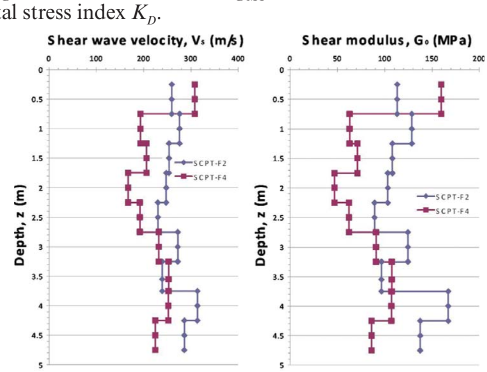


Figure 4. SCPT results at Shenton Park: Shear wave velocity V_s, shear modulus G_0.

– p_0 = the liftoff pressure (σ_{h0} for 'perfect' installation);
– K_0 = lateral earth pressure ratio;
– $p_{5\%}$ = the expansion pressure at a cavity strain of 5% after removal of creep stages;
– $p_{100\%}$ = extrapolation of $p_{5\%}$ to a cavity strain of 100% assuming a linear slope, s;
– $q_{c,\,avg}$ = average tip cone resistance.

Table 1. Summary of SBP test result at Shenton Park site (Schneider 2007).

BH	z (m)	s	ϕ' (°)	ψ (°)	G_{ur} (MPa)	p_0 (kPa)	K_0	$p_{5\%}$ (kPa)	$p_{100\%}$ (kPa)	$q_{c,\,avg}$ (kPa)
1	1.3	0.299	28.4	–4.2	23	20	0.89	0.210	0.514	3.5
2	1.3	0.372	33.9	2.2	26	15	0.67	0.260	0.793	3.5
2	2.3	0.420	37.3	6.5	26	15	0.38	0.252	0.886	3.7
3	2.3	0.420	37.3	6.5	21	20	0.51	0.261	0.920	3.7
1	3.3	0.324	30.3	–2.0	32	80	1.41	0.463	1.22	4.8
2	3.3	0.413	36.8	5.9	30	20	0.35	0.332	1.15	4.8
3	3.3	0.420	37.3	6.5	23	5	0.09	0.273	0.962	4.8
2	3.9	0.377	34.2	2.7	30	35	0.52	0.382	1.18	5.4
1	4.3	0.422	37.5	6.6	34	15	0.20	0.378	1.34	6.6
3	4.6	0.517	44.0	15.1	41	37	0.47	0.669	3.15	7.1

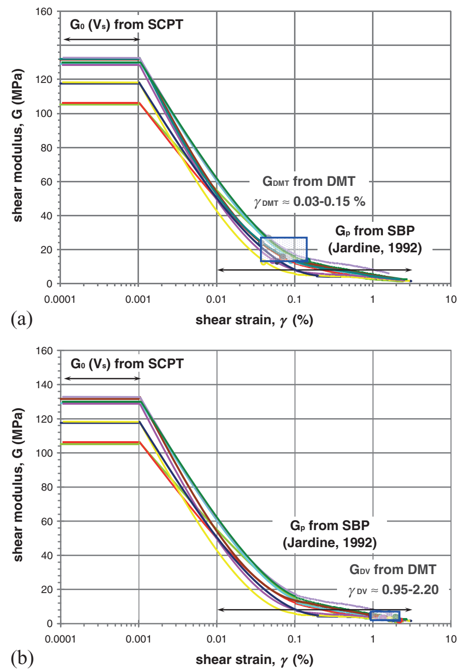


Figure 5. G–γ decay curves from SBP and SCPT tests and G_{DMT}: (a) and G_{DV} ; (b) Values from DMT tests.

As explained by Jardine (1992), SBP data have been used to estimate the non-linear G-γ decay curves at medium and large shear strain (γ > 0.01%), while the small strain stiffness G_0 has been evaluated from shear wave velocity V_s by SCPTs. The intersection of the in-situ G-γ decay curves (as interpreted from SBPTs) and G_{DMT} gives a range of γ_{DMT} values of 0.03–0.15% (Fig. 5a). The intersection of the G-γ curves and G_{DV} gives a range of shear strains $\gamma_{DV} \approx$ 0.95–2.20% (Fig. 5b).

The laboratory G-γ decay curves for reconstituted Shenton Park sand were measured in triaxial tests with local strain measurement and bender elements (Schneider et al. 2008, Amoroso 2011).

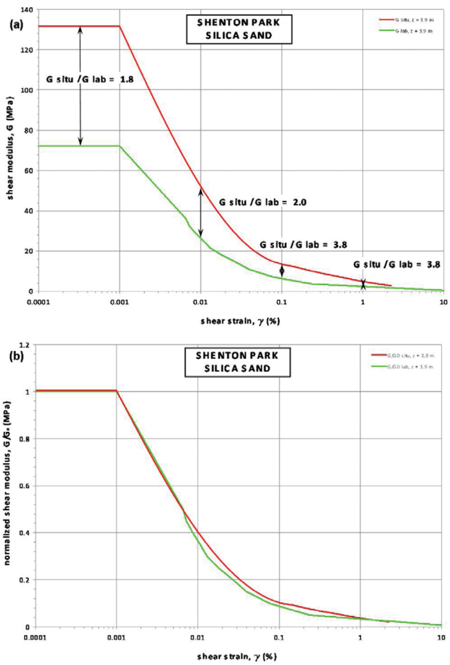


Figure 6. Shenton Park: Comparison (depth 3.9 m) between in situ and laboratory G-γ decay curve (a) and between normalized in situ and laboratory $G/G_{0-\gamma}$ decay curve (b).

These curves are compared on Figure 6a with the in-situ curve derived from SBPTs and Vs data at a depth of 3.9 m. It is seen that the in-situ stiffness varies between 1.8 and 3.8 times the stiffness of reconstituted samples—with (somewhat surprisingly) largest differences observed at higher strain levels. Differences between the normalised stiffness degradation curves of the in-situ and reconstituted sand are much lower, as seen on Figure 6b.

4.2 *Ledge Point*

4.2.1 *Geotechnical tests*

Ledge Point is a site located about 100 km North of Perth, Western Australia, along the coast of the Indian Ocean. It is an example of a coastal aeolian calcareous deposit.

Strength and stiffness parameters have been evaluated using CPTs, SCPTs, DMTs, SBPs, boreholes (BH), laboratory, pile and footing tests, carried out in 2008 (Schneider & Lehane 2010; Lehane 2010), as shown in Figure 7.

Figure 8 presents friction ratios F, CPT net tip resistance q_{cnet}, SBPT parameters and SCPT shear moduli, while Figure 9 shows the DMT parameters: material index I_D, constrained modulus M_{DMT}, friction angle ϕ', horizontal stress index K_D.

These results indicate two main sand layers that repeat throughout the vertical profile; one layer

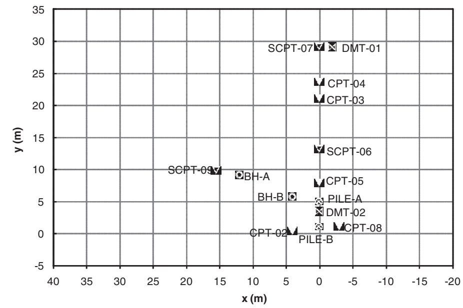


Figure 7. Ledge Point test site (Schneider & Lehane 2010).

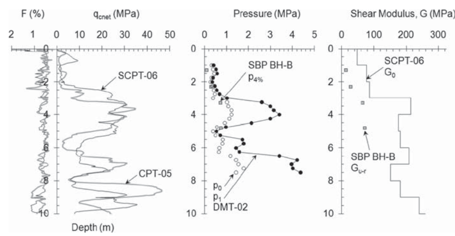


Figure 8. CPT, DMT, SBP and SCPT parameters at Ledge Point: Friction ratio F, tip resistance q_{cnet}, pressure and shear modulus G_0 profiles, (Schneider & Lehane 2010).

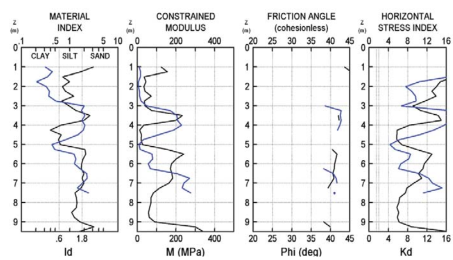


Figure 9. DMT results at Ledge Point: Material index I_D, constrained modulus M_{DMT}, friction angle ϕ', horizontal stress index K_D.

"dense" with a high tip resistance and one layer "loose" with a lower tip resistance. The loose and dense layers are interbedded due to the shifting nature of the sand dunes (Schneider & Lehane 2010).

4.2.2 *G-γ decay curves*

As before, the Jardine (1992) transformation has been used to transform the SBPT data to elemental G-γ decay curves, while the small strain stiffness G_0 has been evaluated from shear wave velocity V_s (obtained at this site using SCPTs).

The intersection of the in-situ G–γ decay curves and G_{DMT} gives a range of γ_{DMT} values of 0.06-0.09% (Fig. 10a) while intersection of the G-γ curves and G_{DV} gives a range of shear strains γ_{DV} of 2 to 2.25% (Fig. 10b).

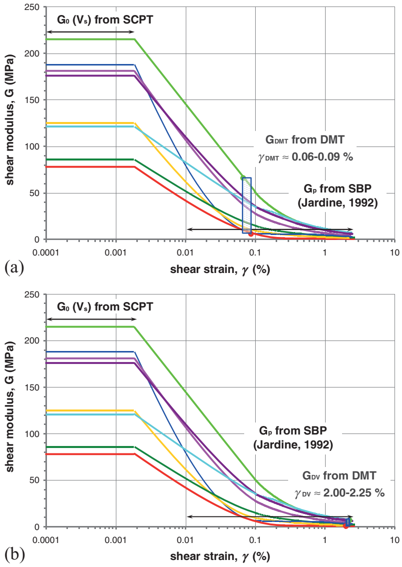


Figure 10. G_s–γ decay curves from SBP and SCPT tests and G_{DMT} (a) and G_{DV} (b) values from DMT tests.

5 CONCLUSIONS

The paper illustrates the potential of using the SDMT to obtain in situ G-γ decay curves. It has been shown, at two sand sites, that the shear modulus equivalent to the standard DMT modulus (G_{DMT}) corresponds to an average elemental stiffness at a shear strain of about 0.1%, while the DMT shear stiffness proposed by Lehane & Fahey (2004), G_{DV}, corresponds to an average elemental stiffness at a shear strain of about 2%. Therefore these two G values combined with the G_0 value determined from V_s can provide a means to construct an approximate element G-γ variation from SDMT data. However, given the variability in the operational strains observed (γ_{DMT} and γ_{DV}), it is clear that further research is further to verify the tentative proposals provided here.

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