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8. ELASTIC PROPERTY CORRECTIONS APPLIED TO LEG 154 SEDIMENT, CEARA RISE[1]

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ABSTRACT

Sediments recovered from Ocean Drilling Program (ODP) holes undergo elastic rebound and physical expansion when recovered from great depths below the seabed (about 75 m). This expansion contributes to the artificial "growth" of the composite depth section (Hagelberg et al., 1992). Sediment elastic properties, derived from one-dimensional consolidation tests, are used to correct the expanded sediment column back to in situ values. The property that controls this effect is the sediment elastic rebound (C_r), which is a simple function of the effective stress or depth below the seabed and sediment type. For Leg 154 sites, 90% to 95% of the composite section "growth" is attributed to elastic rebound of the sediment. The remaining "growth" is likely caused by intervals of sediment flow-in, identified in the visual description of the split cores.

The composite depth scale, although artificially expanded, is an excellent tool for building a composite stratigraphy at one site. However, caution should be used when applying this depth scale for the construction of synthetic seismograms, for calculation of mass accumulation rates, and for any analyses that requires true sediment thickness. For these applications, corrections to the composite depth section are recommended.

INTRODUCTION

Deep-sea sediments have both elastic and plastic deformation properties. The plastic properties are the predominant control on the "permanent" consolidation or the compaction history of sediments. The elastic properties represent the recoverable strain within sediment when stresses are removed. These plastic and elastic components of consolidation are best described using Terzaghi's one-dimensional consolidation theory (Terzhagi, 1943). The theory defines a log-linear function of porosity reduction with increasing stress and is called the "virgin compression" curve (Fig. 1). The slope of this log-linear curve is the coefficient of compression (C_c). This type of function was empirically determined by petroleum engineers in the early 1930's for estimation of porosity-depth functions in sedimentary basins (Athy, 1930). However, the Athy functions can only be crudely applied to sediment under gravitational loading because the functions are described for a few ranges of sediment types defined by grain size. These empirical functions also do not separate the porosity reductions into their elastic and plastic components.

In addition to virgin compression, the Terzaghi theory also includes a description of sediment elastic expansion when stresses are reduced, for example, during the recovery of samples from below the seafloor. This study describes the application of the elastic rebound as the largest component of the "growth" of the composite depth scale. The elastic rebound is also used to correct laboratory-measured index properties to equivalent in situ values.

METHODS

Application of the Terzaghi theory is performed by testing samples under conditions of one-dimensional consolidation. In this study, back-pressured consolidometers were used on samples trimmed to a diameter of 5.1 cm and a height of 1.9 cm. Incremental loads were applied at the end of primary consolidation using a load increment ratio of 1. Figure 1 is an example of results from a typical consolidation test. The amount of elastic rebound in a core taken from any depth below the seafloor is calculated using the log-linear slope of the elastic rebound portion of the consolidation curve (C_r), following the derivation of MacKillop et al. (1995):

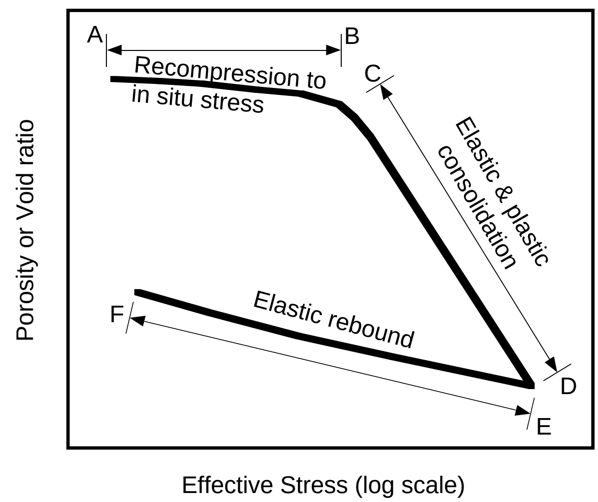

Figure 1. Idealized consolidation curve showing the recompression of the sample back to its in situ stress (A to B); the virgin compression curve, which represents the sediment's natural compaction function (C to D); and the elastic rebound, which represents the sediment's expansion behavior during stress release (E to F).

$$\Delta e = C_r \log (P_o') \qquad (1)$$

where P_o' is the vertical effective overburden stress (i.e., stress relief resulting from sampling) and Δe is core expansion represented in terms of void ratio change.

The change in void ratio resulting from stress relief and subsequent core expansion is converted to lengthening of the core (ΔL) by:

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$$\Delta L = \Delta e\,(L_o - nL_o) \tag{2}$$

where n is the core porosity, and L_o is the recovered length of the core. For the sites analyzed here, Δe and ΔL are calculated for each core. ΔL resulting from elastic rebound is then accumulated with depth below seafloor (mbsf) and compared with the expansion of the composite depth (mcd) scale. To correct mcd scale for this expansion, the incremental ΔL values are subtracted.

The elastic rebound of the sediment caused by the sampling process causes the bulk density (ρ), dry density (ρ_d) and porosity (n) to change. As elastic rebound expands the core during sampling, the bulk density and dry density decrease and the porosity increases. The coefficient of rebound can be used to correct these data back to their in situ values. The correction is made by calculating the change in void ratio for each interval where index properties were measured and then converting the new corrected void ratio to ρ, ρ_d, and n using phase relationships (see, for example, Holtz and Kovacs, 1981).

The corrected dry density is a critical component in the determination of sediment mass accumulation rates. Similar to bulk density, dry density follows a log-linear relationship with pressure (or depth below seafloor). Appropriate log-linear functions are presented for each site for use in mass accumulation rate calculations.

RESULTS

Four consolidation tests were completed on samples from Leg 154, Hole 929D; two tests from each of two depth intervals. Duplicate tests were run for Sample 154-929D-6H-4, 135–150 cm, and Sample 154-929D-6H-5, 135–150 cm (Table 1).The test results show good definition of virgin compression and elastic rebound (Fig. 2). The elastic rebound (C_r) from these tests show small variation from 0.11 to 0.13. The average rebound (0.12) is used to calculate the change in void ratio caused by the effective stress relief during sample recovery for all sites (Eq. 1). The consolidation test results also are used to define the preconsolidation stress (P_c') which can be used to determine the state of consolidation of the sediment. In the tests completed for Leg 154 samples, P_c' values are much less than the existing overburden stress, calculated using either uncorrected or corrected bulk density. The resulting overconsolidation ratio values are about 0.3–0.5, suggesting underconsolidation of the sediment column.

Core Length and Depth Scale Corrections

The change in void ratio caused by elastic rebound is converted to an equivalent change in the length of each core (Eq. 2). This cumulative core lengthening, calculated solely on elastic rebound, can account for more than 95% of the "growth" of the mcd scale (Moran, 1995). The mcd scale is ideal for construction of complete stratigraphic sections for paleoceanographic studies. However, because of its artificial growth, it does not represent a true depth below the seafloor. All depth scales used in drilling suffer from some error. The mcd scale, however, has a consistent and increasing error with depth. Thus, correction of this scale to a more realistic depth is desirable. In this study, the elastic core expansion is used to correct the mcd. First, the elastic core expansion caused by stress relief is added together cumulatively with depth below the seafloor. It is then plotted as a function of depth below the seafloor to obtain a "growth" function in terms of the mbsf scale. For all sites, this elastic core expansion results are best approximated using a simple power function with mbsf (Fig. 3). The power function takes the form of $y = ax^b$. At each site, this power function can be applied to the expanded mcd scale to correct for elastic core expansion (E). To determine the corrected mcd scale, the procedure is as follows.

Table 1. Summary of consolidation test results.

Test	Core, section, interval (cm)	C_c	C_r	P'_c	OCR
	154-929D-				
1	6H-4, 135–150	0.45	0.11	140	0.5
2	6H-4, 135–150	0.42	0.12	110	0.4
3	6H-5, 135–150	0.36	0.13	80	0.3
4	6H-5, 135–150	0.35	0.12	95	0.3

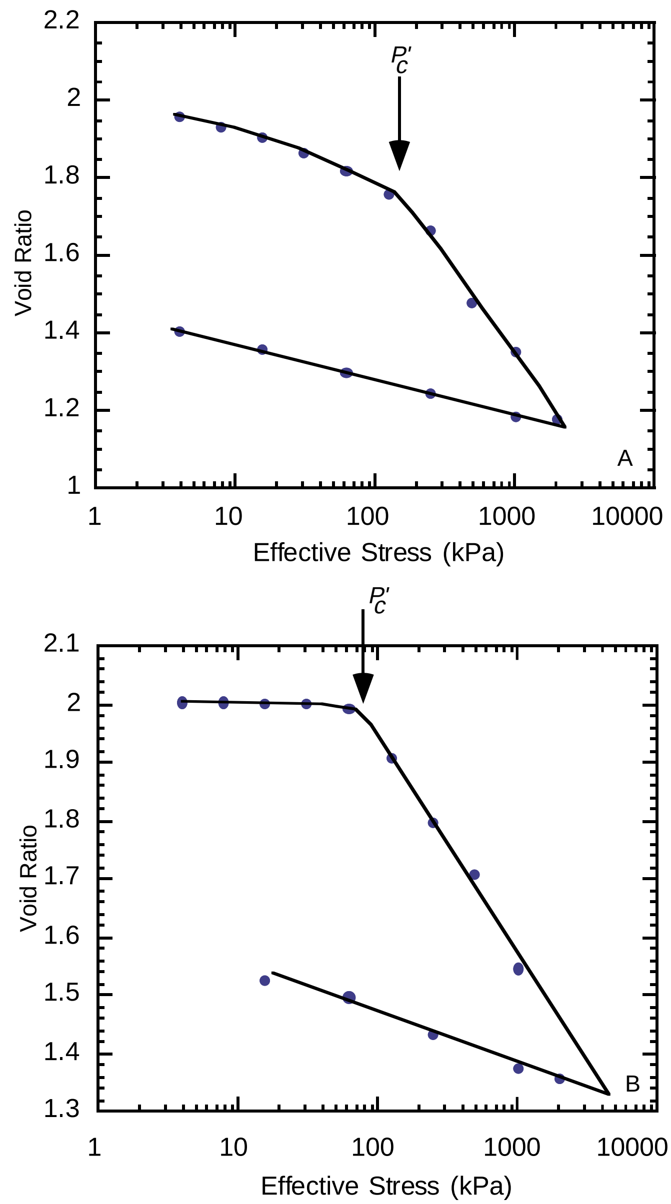

Figure 2. Consolidation curve test results for Sample 154-929D-6H-4, 135–150 cm (top panel), and Sample 154-929D-6H-5, 135–150 cm (bottom panel). The results show good definition of virgin compression and elastic rebound.

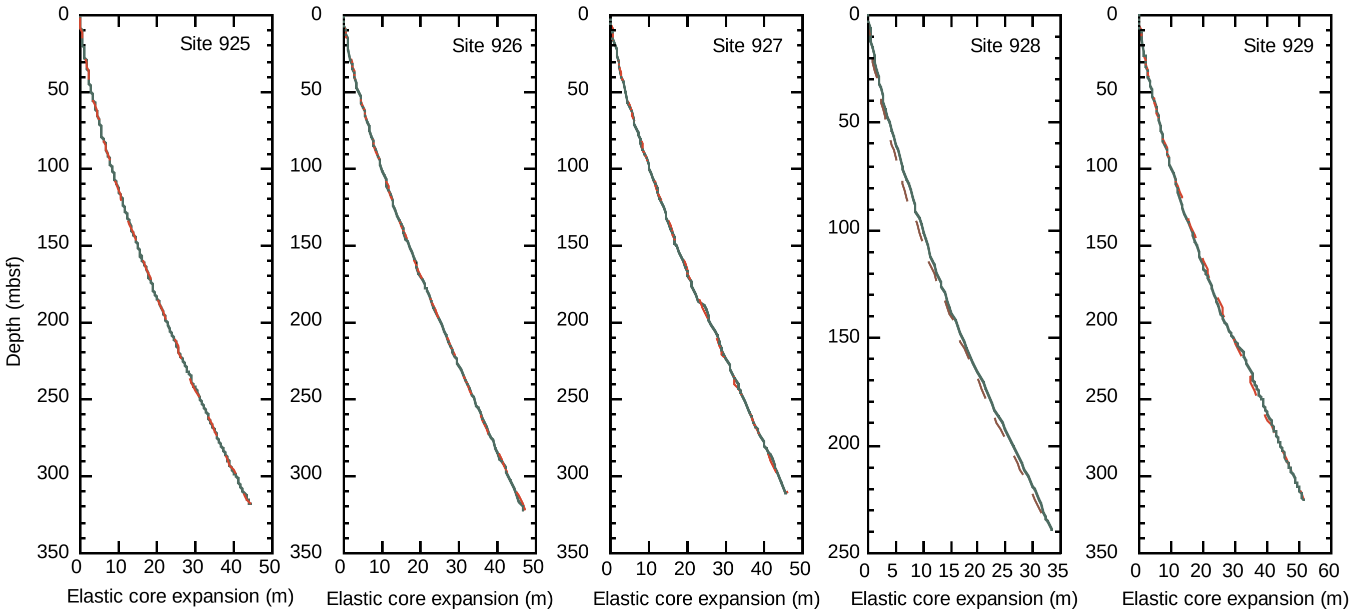

Figure 3. Elastic core expansion plotted (solid line) vs. depth using the mbsf scale. At all sites, the calculated expansions follow a simple power function (dashed line) that is used to correct the mcd scale.

Table 2. MCD correction coefficients for Equation 3.

Site	Elastic rebound coefficient a	Elastic rebound coefficient b
925	0.011	1.44
926	0.021	1.33
927	0.003	1.33
928	0.010	1.48
929	0.020	1.40

1. Using the CORELOG.MCD text file from the CD-ROM (of Curry, Shackleton, Richter, et al., 1995) or any data file that contains both mbsf and mcd, calculate the elastic core expansion using Equations 1 and 2.
2. Apply a power function to the cumulative profile:

$$E = a \times \text{mbsf}^{b} (\text{m}) \quad (3)$$

where a and b are coefficients determined from the power function for each site (Table 2; Fig. 3).
3. Calculate the corrected mcd scale (over depth intervals where more than one hole contributes to the mcd) in units of meters using

$$\text{mcd (corrected)} = \text{mcd} - E \quad (4)$$

The corrected mcd scale is close to the mbsf scale, which represents a more realistic true depth scale. This comparison is best shown by plotting the mbsf scale against the corrected mcd showing good linear correlation at each site (e.g., Hole 925A; Fig. 4).

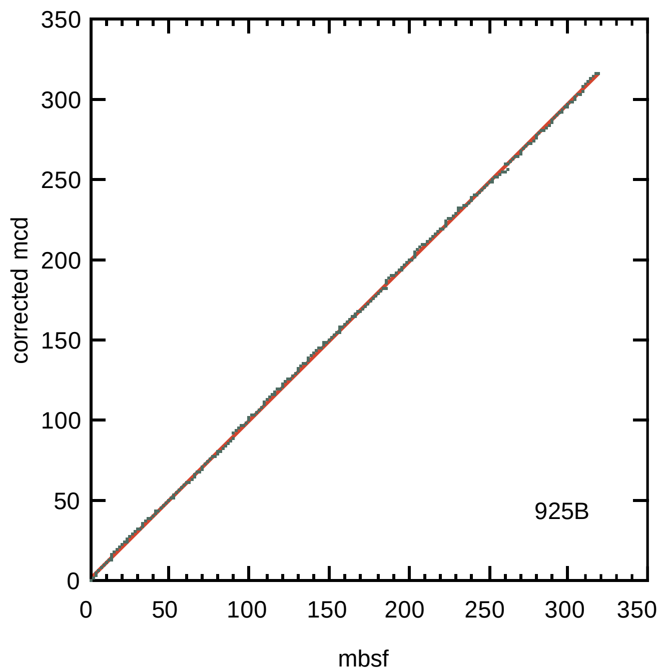

Figure 4. Comparison of the corrected mcd scale with the mbsf scale shows an almost one-to-one correlation.

Index Property Corrections

The sediment elastic rebound causes changes in void ratio, porosity, bulk density, dry density, and water content during the sampling process because of an increase in volume. The magnitude of these changes increases with depth below the seafloor because the elastic response is greater with larger changes in effective stress. For Leg 154 sediments, the elastic rebound becomes significant deeper than 75 mbsf. Very little expansion occurs in the upper tens of meters because of the small changes in effective stress during sampling. Thus, standard oceanographic piston core samples will not be significantly affected by this process, except in environments where dissolved gas is present in the pore fluids.

Corrections to these index properties are made using the change in void ratio (*e*) equation developed for correction of the core length (Eq. 1). At each index property measurement interval, Δe is calculated and a new corrected void ratio (e_c) is determined. The index properties can then be determined using the corrected void ratio and two other properties that do not change with elastic rebound: grain density (ρ_g or specific gravity, G_s) and pore fluid density (ρ_w). The following phase relationships are used to determine the corrected properties of bulk density (ρ), dry density (ρ_d) and porosity (n):

$$\rho = \{(\rho_g + e_c)/(1 + e_c)\}\rho_w \tag{5}$$

$$\rho_d = \rho_g/ (1 + e_c) \tag{6}$$

$$n = e_c/ (1 + e_c) \tag{7}$$

Corrections to bulk density and dry density can be made using these equations with the calculated rebound-corrected void ratio. At each site, the corrected bulk density values are larger than the laboratory-measured values and the difference between the measured and corrected increases with depth (e.g., Fig. 5). It is appropriate to use corrected values for applications in synthetic seismograms, determination of in situ stress conditions, and for correlation with downhole logging data.

Corrected dry density values are important for more accurate determination of mass accumulation rates. For each site, the corrected dry density values were calculated. These data show a consistent log-linear relationship with depth (pressure), as predicted by the Terzaghi one-dimensional consolidation theory (Fig. 6). Two logarithmic approximations were fitted to the data at each site to approximate the shallow sediment section (e.g., 0 to 20 mbsf; Fig. 6B) and the deeper sediment section (20 mbsf and greater; Fig. 6A). The data were divided into two depth intervals for each site because variation in sediment composition causes deviations from the log-linear functions and an approximation over the entire depth range can lead to predictions of very low and unrealistic dry density values at the seafloor. These approximations were determined for each Ceara Rise site (Table 3) and are recommended for mass accumulation rate determinations.

SUMMARY

During recent paleoceanographic drilling legs, the use of composite depth sections (using the mcd scale) has significantly improved the construction of complete stratigraphic sequences at key sites. However, it has been shown that the mcd scale artificially expands the depth scale. MacKillop et al. (1995) and Moran (1995) have shown that most of this artificial growth can be attributed to the elastic rebound of the sediment resulting from stress-relief during the sampling process. Using the measured elastic rebound properties, corrections to the mcd scale can be made for the Ceara Rise sites. In addition, the elastic rebound causes changes in some of the index properties of the recovered samples. In a similar manner to the depth correction, the elastic rebound properties are used to correct laboratory index property and multisensor track data so that they more closely represent in situ values.

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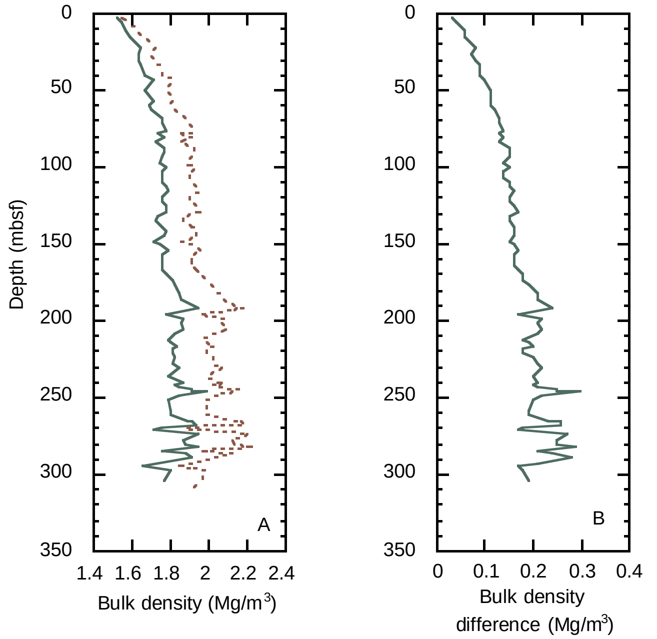

Figure 5. Laboratory-measured bulk density (solid curve) shown with rebound-corrected bulk density (dashed curve) for Hole 927B (left panel); and a plot of the difference between uncorrected and corrected and bulk density (right panel) showing its increasing magnitude with depth (stress). Other hole data can be corrected following the same procedures.

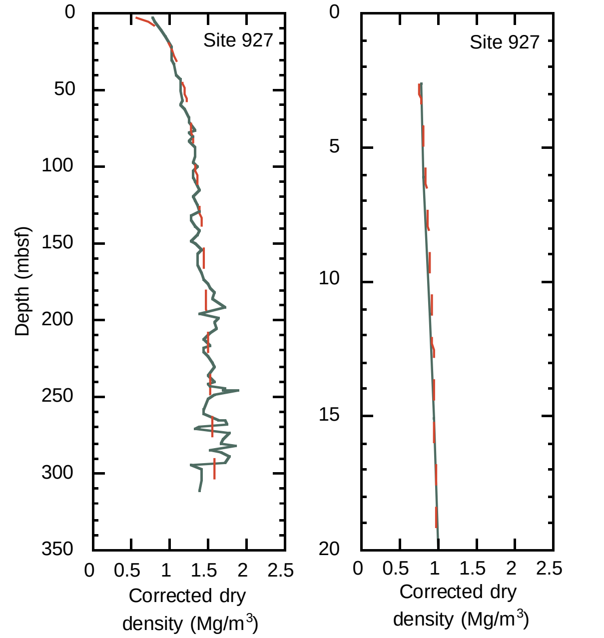

Figure 6. Rebound-corrected dry density plotted for Site 927. A log-linear function represents a good fit to these data and is recommended for use in mass accumulation rate determinations. For depths greater than 20 mbsf, use the log-linear function of left panel and for depths less than 20 mbsf, use the log-linear function of right panel. Similar corrections and curve fits are completed for each site (Table 3).

Table 3. Corrected dry density functions for Sites 925–929.

Site	Depth interval (mbsf)	Corrected dry density function
925	0–20	1.48 + 0.13 log(d)
925	20–270	0.04 + 0.60 log(d)
926	0–6	0.74 + 0.08 log(d)
926	6–230	0.42 + 0.46 log(d)
927	0–20	0.73 + 0.11 log(d)
927	20–130	0.35 + 0.50 log(d)
928	0–5	0.74 + 0.10 log(d)
928	5–150	0.40 + 0.48 log(d)
929	0–210	0.37 + 0.51 log(d)

Note: d = depth (mbsf).