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Submarine Slope Stability of a Fjord Delta: Bella Coola, British Columbia
La stabilité des pentes dans le delta fjord de Bella Coola, Colombie-Britannique
Stabilität der untermeerischen Abhänge Im Fjord-Delta Bella Coola, British Columbia

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Résumé de l'article

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SUBMARINE SLOPE STABILITY OF A FJORD DELTA: BELLA COOLA, BRITISH COLUMBIA

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ABSTRACT Recent evidence indicates that the submarine slopes of the Bella Coola Delta, a fjord delta in British Columbia, are subject to mass movements. Mass movements originate in the source areas of chutes (gullies) and transfer coarse sediment downslope. Stability analyses indicate that earthquakes, depositional loading and wave loading are capable of causing slope failures in chute source areas. Gas generation and tidal drawdown appear to reduce sediment strength by increasing pore water pressures, increasing the potential for failures initiated by other mechanisms. Failure related to slope oversteepening at distributary mouths would require much steeper slopes than those encountered. The most unstable areas are those at distributary mouths where most of the mechanisms of failure generation could occur simultaneously. With the exception of earthquakes, the failure mechanisms examined would result in high frequency, low magnitude slides that are most likely to occur in spring and summer. Earthquakes would cause high magnitude, low frequency failures.

RÉSUMÉ *La stabilité des pentes dans le delta fjord de Bella Coola, Colombie-Britannique.* Des observations récentes démontrent que les pentes sous-marines du delta de Bella Coola sont sujettes à des mouvements de masse. Ces mouvements prennent leur origine dans les zones de formation de ravines et provoquent le transfert des sédiments grossiers vers le bas. Les analyses de stabilité montrent que les tremblements de terre, la charge d'accumulation et la charge des vagues peuvent causer des décrochements. La formation de gaz et la baisse des marées semble réduire la résistance au cisaillement des sédiments en augmentant la pression interstitielle, multipliant ainsi les possibilités de ruptures amorcées par d'autres mécanismes. Les pentes observées à l'embouchure des effluents ne permettent pas qu'il y ait ruptures provoquées par une trop forte inclinaison. Les régions les plus instables sont situées à l'embouchure des effluents où la plupart des mécanismes à l'origine des décrochements peuvent s'exercer simultanément. Sauf en ce qui à trait aux tremblements de terre, les mécanismes étudiés provoqueraient de fréquents glissements, mais de faible importance, plus susceptibles de se produire au printemps et en été. Par contre, les tremblements de terre seraient à l'origine de glissements importants, mais plus rares.

ZUSAMMENFASSUNG *Stabilität der untermeerischen Abhänge im Fjord-Delta Bella Coola, British Columbia.* Neuere Belege zeigen, dass die untermeerischen Abhänge des Bella Coola-Deltas, einem Fjord-Delta in British Columbia, Bewegungen von solidem Material ausgesetzt sind. Die Bewegungen von solidem Material gehen von Schluchten aus und befördern grobe Sedimente hangabwärts. Stabilitäts-Analysen zeigen, dass Erdbeben und die Belastung durch Ablagerung und Wellen Hangbrüche Rutschungen bewirken können. Die Bildung von Gas und das Nachlassen der Gezeiten scheinen die Sediment-Stärke zu verringern, indem sie den Druck von Poren-Wasser erhöhen und damit die Möglichkeit für Brüche, die durch andere Mechanismen eingeleitet wurden, noch erhöhen. Die vorgefundenen Abhänge sind nicht steil genug, um die Brüche auf zu steile Abhänge an den Mündungen der Abflüsse zurückzuführen. Die am wenigsten stabilen Gebiete befinden sich an den Mündungen der Abflüsse, wo die meisten Mechanismen, die Brüche provozieren können, gleichzeitig auftreten können. Mit Ausnahme der Erdbeben würden die untersuchten Bruchmechanismen zu häufigen aber geringfügigen Erdrutschen führen, die am ehesten im Frühling und Sommer vorkommen. Erdbeden würden zu bedeutenderen aber selteneren Erdrutschen führen.

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INTRODUCTION

It has been increasingly apparent in recent years that mass movements are very common on submarine slopes of deltas. Evidence from fjord deltas (*e.g.* Prior *et al.*, 1983) suggests that these processes are of fundamental importance to subaqueous morphologic and depositional patterns. In addition, large events can cause considerable damage to docks, jetties and other structures (Prior *et al.*, 1983). Recently, attention has begun to focus on a critical aspect of fjord delta mass movements, the causes of slope failure (*e.g.* Johns *et al.*, 1986; Karlsrud and Edgers, 1982).

The Bella Coola River delta, a fjord delta in coastal British Columbia, is characterized by submarine features (Fig. 1) indicative of submarine slope failures (Kostaschuk and McCann, 1987). Kostaschuk and McCann (1987) have shown that the delta slope consists of separate, though related, mass-movement systems. The steeply sloping (2.3° to 15°), proximal, sandy delta front is dominated by large chutes (gullies) (Fig. 2a) with associated source areas and depositional zones (Fig. 2b) that are deformed by shallow rotational slides (Fig. 2c). The chute system is the primary mechanism by which coarse sediment is transferred downslope. Farther offshore, the gently sloping (0.5° to 2.3°), muddy prodelta is characterized by large, deep-seated rotational slides (Fig. 2d). Kostaschuk and McCann (1987) suggest that delta front failures begin in the very steep (8° to 15°) chute source areas as slides and sediment is transferred downslope in the channels via debris flows, coming to rest in depositional zones. Progradational loading in the depositional zones is believed to be a primary factor in the initiation of prodelta slides.

It is clear that failures in the delta front chute source areas in Bella Coola are directly linked to mass movements further downslope, and that in order to understand the causes of submarine failure on the delta we must focus on the source areas. Prior and Coleman (1983) outline a number of environmental factors that may cause initial submarine slope failures, including earthquakes, slope oversteepening, depositional loading, wave loading, gas generation and tidal drawdown. The purpose of this paper is to examine the roles played by these factors in the generation of chute source area failures in Bella Coola.

SEDIMENT CHARACTERISTICS

GRAIN SIZE

The median grain size (M_d), sorting (σ_I) (Folk, 1974) and % clay were determined, using sieve analysis, for 24 grab samples from the delta front and two borehole samples (Table I). Sediments are coarsest and most variable in the

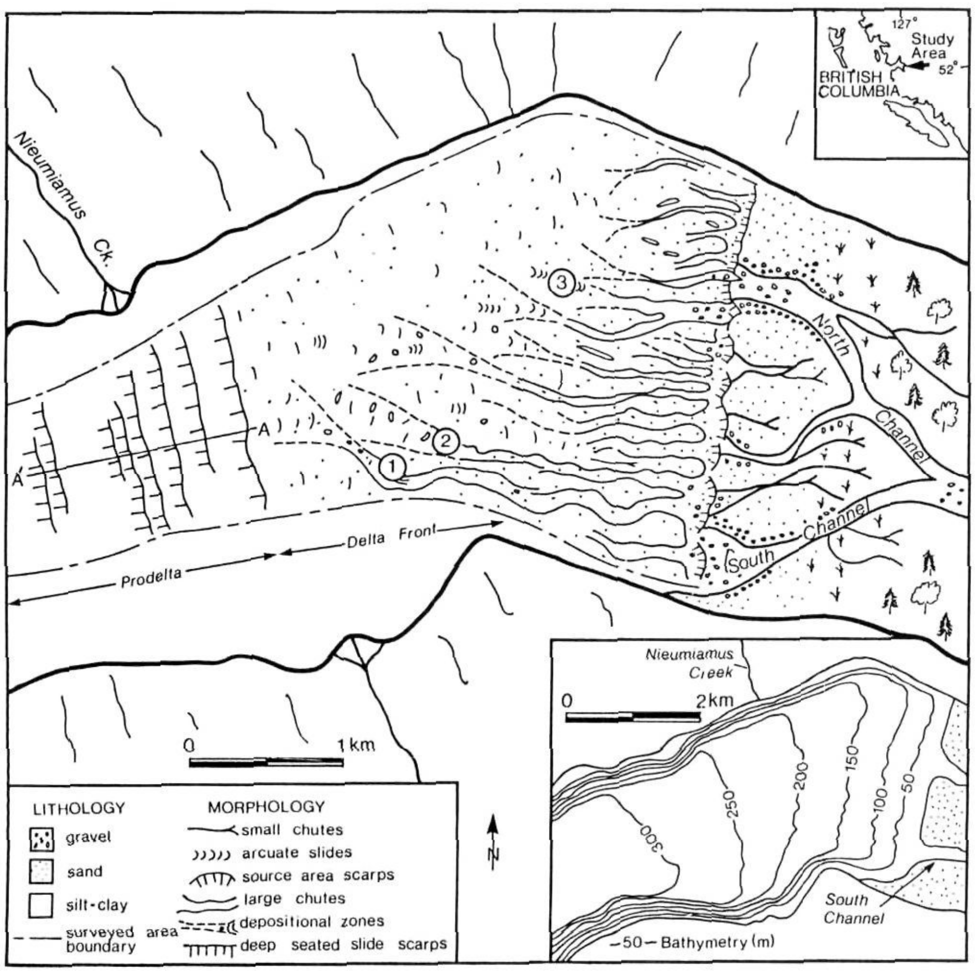

FIGURE 1. Interpretive map of the subaqueous Bella Coola Delta, based on hydrographic charts, fathometer profiles, sidescan sonar records, seismic profiles, aerial photographs and bottom samples. Letters and numbers mark locations of sidescan and seismic records illustrated on Figure 2.

Interprétation cartographique des profondeurs du delta de Bella Coola, fondée sur les cartes hydrographiques, les profils des échosondages, les enregistrements sonar horizontaux, les profils sismiques, les photographies aériennes et les échantillons de fond. Les lettres et les chiffres donnent l'emplacement des enregistrements sonar et horizontaux illustrés à la figure 2.

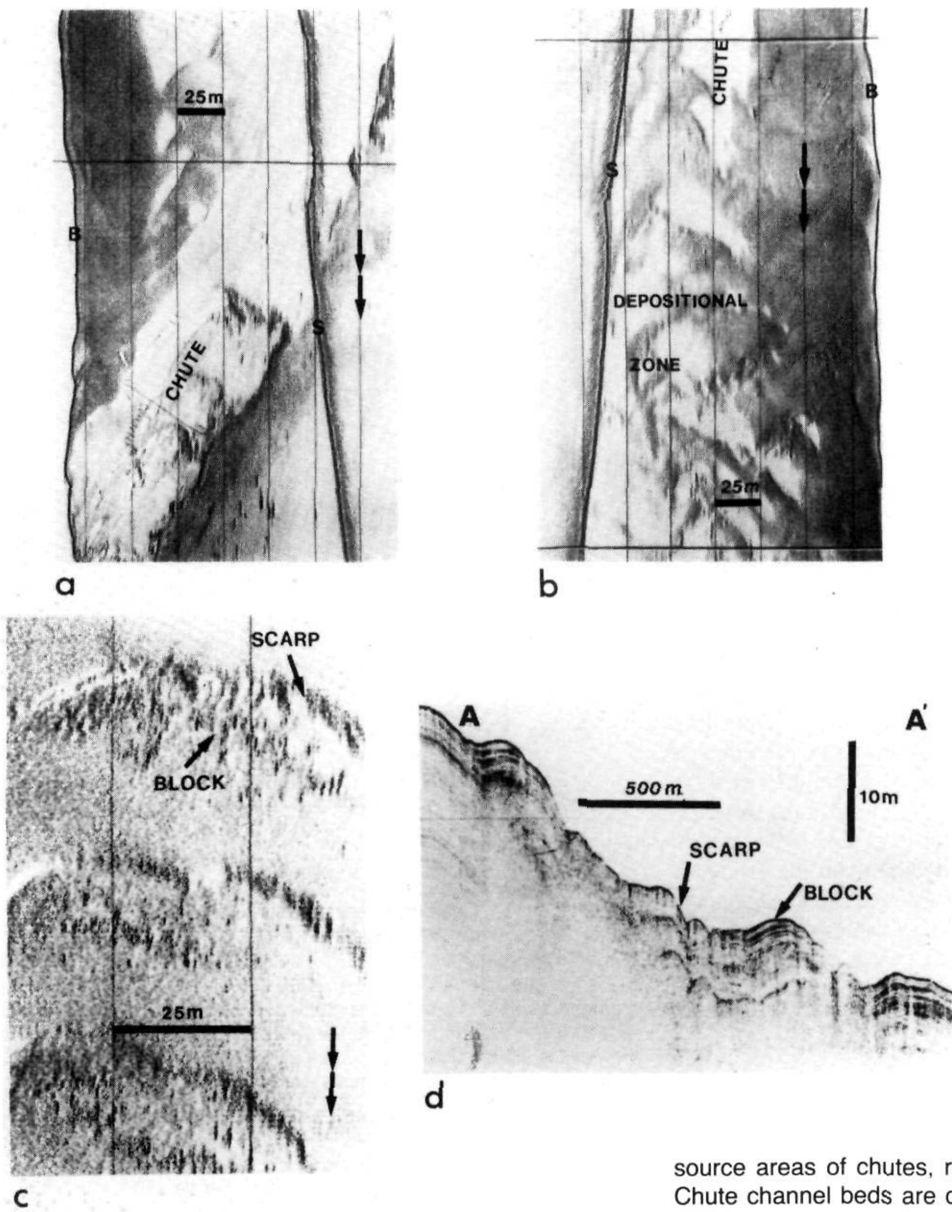

FIGURE 2. Sidescan records of the delta front (a-c) and seismic profile (d) of the prodelta. On the sidescan records B refers to the trace of the sea bed, S to the sea surface and the double arrow points downslope. (a) A sinuous chute channel (No. 1 on Fig. 1); the signal is from the left. (b) Depositional zone of a chute (No. 2 on Fig. 1); signal is from the right. (c) Small arcuate rotational slides on the delta front (No. 3 on Fig. 1). (d) 3.5 kHz record of large rotational slide (AA' on Fig. 1).

Enregistrements des balayages horizontaux au front du delta (a-c) et profil sismique (d) en avant du delta. La lettre B sur les balayages horizontaux se rapporte au lit marin, S à la surface et la flèche double pointe vers l'aval. a) Chenal de ravine sinueux (n° 1, sur la fig. 1); le signal vient de la gauche; b) zone d'accumulation d'une ravine (n° 2, sur la fig. 1); le signal vient de la droite; c) petits glissements de rotation au front du delta (n° 3 sur la fig. 1); d) enregistrement de 3.5 kHz d'un important glissement de rotation (AA' sur la fig. 1).

TABLE I

Median grain size (M_d), sorting (σ_I) and % clay for selected delta front sand samples

Sample	M_d (ø-scale)	σ_I (ø-scale)	% clay
Par 82-006	1.0	0.8	1
007	2.2	1.2	1
008	2.9	0.9	1
010	3.2	0.8	4
011	3.6	1.7	3
012	3.6	1.4	5
DH5 (3.7 m.)	4.2	1.8	10
DH12 (3.7 m.)	4.4	2.0	11

source areas of chutes, ranging from gravel to coarse silt. Chute channel beds are coarse upslope (gravel to medium sand), becoming finer offshore (fine to very fine sand). Depositional zone sediments are fine and very fine sand. Sorting varies from moderate to poor and clay contents are low. The boreholes of Cook *et al.* (1977, 1982) reveal that much of the sediment overlying bedrock on the southern edge of the delta is composed of loose, uniform fine sand and sandy silt with clay contents of 10-11% and water contents ranging from 25-40%. Some shells, wood and gravelly sand were also noted.

STRENGTH

The strength, or shear resistance, of unconsolidated sediment depends on a number of factors, the most important being the cohesive and frictional properties of the material (Selby, 1982). Strength can be described by the Mohr-Coulomb failure criteria for total stresses (Selby, 1982, p. 51) as follows:

$$s = c + \sigma \tan \phi \quad (1)$$

where: s is the shear strength at any point in the sediment
c is the cohesion
σ is the total normal stress imposed by the weight of solids and water above the point
ø is the friction angle

For effective stresses, the criteria becomes:

$$s = c' + (\sigma - u) \tan ø' \quad (2)$$

where: c' is effective cohesion
u is pore water pressure at the point
ø' is the effective friction angle

Strength parameters are usually evaluated by laboratory tests on samples (*e.g.* Hunt, 1984).

The only geotechnical information for the Bella Coola delta is that provided by Cook *et al.* (1977, 1982), consisting of triaxial tests from two borehole cores. Consolidated, undrained, triaxial tests (Selby, 1982, p. 130) were used to determine values of total stress and effective stress cohesion and friction angle. In this procedure the sample is allowed to consolidated under an effective stress corresponding to the *in situ* effective stress. The sample is then sheared under conditions of no drainage and pore water pressures measured. For Bella Coola, two tests under different lateral pressures, were carried out for two adjacent samples from each borehole. The test results were plotted as Mohr circles for both total and effective stresses. An example from one borehole is provided on Figure 3. The results indicate that the sediment is cohesionless. The total stress friction angles (ø) were 27° and 28° and the effective stress friction angles (ø') were 35° and 36°. These values seem somewhat high for sandy silt (*e.g.* Hunt, 1984) suggesting some densification during sampling (Cook *et al.*, 1982). These friction angles are likely minimum values for Bella Coola and, all other things being equal, the coarser sands and gravels should be higher. A saturated unit weight of $\gamma = 1.60$ Mgm^{-3} was found for two samples analysed (Cook *et al.*, 1982).

A.

B.

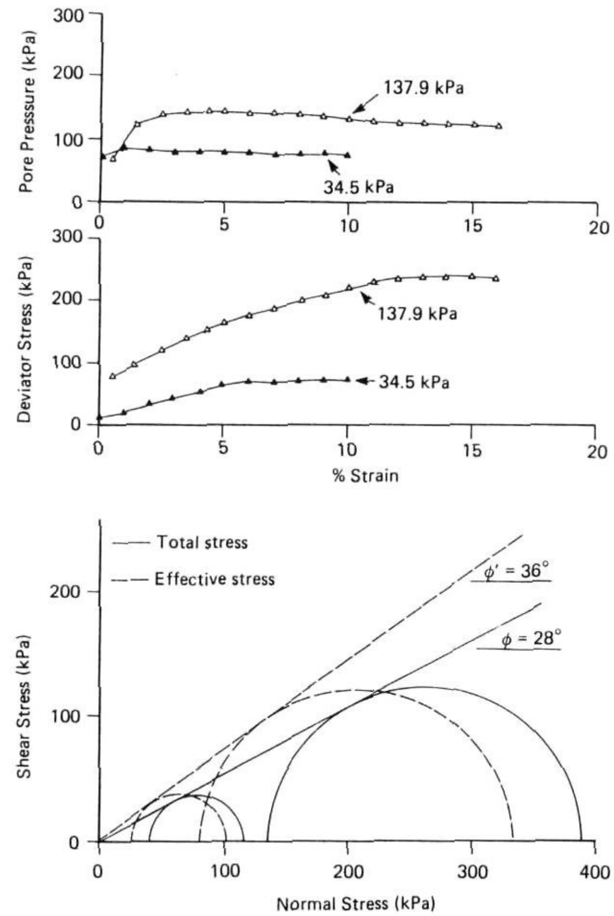

FIGURE 3. A) Results of back-pressured, consolidated, undrained triaxial compression tests, with pore pressure measurements, on borehole samples of sandy silt. Consolidation pressures of 34.5 kPa (5 psi) and 137.9 kPa (20 psi) were used and a constant back-pressure of 69 kPa (10 psi) maintained. Actual pore water pressures at failure are determined from the measured pore pressures minus the back-pressure. Data from Cook et *al.* (1982). B) Mohr diagrams, constructed from the triaxial tests, for total and effective stresses.

A) Résultats des tests de compression à trois axes de types contre-pression et compaction de matériel non drainé, ainsi que des mesures de pression interstitielles, sur les échantillons de silt sableux. Des pressions de compaction de 34,5 kPa (5 psi) et de 137.9 kPa (20 psi) ont été appliquées et une contre-pression constante de 69 kPa (10 psi) maintenue. Les pressions interstitielles réelles au moment de la rupture sont déterminées à partir des mesures de pressions interstitielles moins la contre-pression (données de Cook et al. *1982). B. Diagramme de Mohr dressé à partir des tests de contraintes totale et réelle à trois axes.*

CAUSES OF CHUTE SOURCE AREA FAILURES

In the following analyses, the distinction is made between drained and undrained mechanisms of submarine failure (Morgenstern, 1967; Algamor and Wiseman, 1982). The shear strength of sediment depends on the conditions of drainage during shear and the time required for draining. During undrained failure, excess pore pressure develops in the sediment more rapidly than it can be dissipated. In drained failure, excess pore pressure does not develop because dissipation occurs. Undrained failure is considered a short term process and drained failure a long term process. Sediment strength during undrained failure is expressed in terms of total stresses and in drained failure as effective stresses.

SLOPE OVERSTEEPENING

Submarine slopes can be oversteepened, so that gravitational stress exceeds sediment strength, by differential progradation of a surface (more rapid deposition upslope) or under-cutting at the base of a slope (Prior and Coleman, 1983). The stability of a slope with respect to gravitational stresses alone can be assessed using infinite slope analysis. This method of analysis assumes a shallow, long slide of uniform thickness on a slope of constant angle and infinite extent (Skempton and DeLory, 1952), conditions usually approximated in subaqueous environments. The factor of safety, F, of a submarine slope can be expressed as a ratio of sediment strength over the shear stress on the slope. When F exceeds 1, the slope is considered to be stable. For fully undrained conditions in cohesionless material (c = 0), and assuming that the pore pressures developed during the triaxial tests are identical to the pore pressures developed in the sediment

(Almagor and Wiseman, 1982), the factor of safety is (Algamor and Wiseman, 1982):

$$F = \tan ø / \tan \beta \qquad (3)$$

where: ø is the total stress friction angle
β is bottom slope

For fully drained conditions in cohesionless sediment and assuming no excess pore pressure, the factor of safety is (Almagor and Wiseman, 1982):

$$F = \tan ø' / \tan \beta \qquad (4)$$

where: ø' is effective stress friction angle

For the sandy silt layers analysed in Bella Coola, it is unlikely that either fully drained or fully undrained conditions will occur during slope oversteepening. Sandy silts tend to be intermediate in permeability between permeable sands and gravels and impermeable clays (Hunt, 1984) and as such slow pore pressure dissipation will probably occur. However, the effective and total stress friction angles should serve as useful upper and lower strength bounds for this process.

It is apparent from Equations 3 and 4 that fully drained and undrained slope failures will occur only when bottom slope exceeds the friction angle of the sediments. The maximum slope measured (15°) in Bella Coola is much less than both the total and effective stress values of friction angle and as such the slopes encountered are considered stable. However, near distributary mouths in the source areas of chutes, slopes may be temporarily oversteepened to angles exceeding the friction angle of sediments as the river mouth builds seaward during river floods. The mean annual discharge of the Bella Coola River is 181 $m^3 s^{-1}$ and typical snowmelt spring flood discharges exceed 300 $m^3 s^{-1}$. In addition, autumn and early winter floods up to 1500 $m^3 s^{-1}$ can occur during rainstorms on a ripe snowpack (Hart, 1981). Flood discharges transport large volumes of sand and gravel bedload to distributary mouths (Western Canada Hydraulics, 1976), potentially increasing slope angles and producing sliding in chute source areas.

EARTHQUAKES

Earthquakes are an important mechanism of short term, undrained failure on submarine slopes (Morgenstern, 1967). The undrained approach for earthquake-induced failure is more appropriate than the drained approach because the abruptness of the earthquake shock renders impossible the drainage of pore water from the sediment, even if the sediment is very permeable (Algamor and Wiseman, 1982). Earthquake accelerations act both vertically and horizontally, but for purposes of stability analysis, the vertical component is assumed to be small relative to the horizontal and is ignored (Almagor and Wiseman, 1982). Earthquakes increase the stress on a slope by introducing a horizontal body force k, expressed as a fraction of gravity, which acts on the whole sediment-water mass and increases pore water pressure.

Algamor and Wiseman (1982) use infinite slope analysis to assess the effects of earthquake accelerations on undrained failure. The force equilibrium along a potential failure plane is given by (Algamor and Wiseman, 1982):

$$\tan ø = 0.5 \sin 2\beta + k(\gamma / \gamma')\cos^2 \beta \qquad (5)$$

where: γ' is the buoyant unit weight of the sediment, $= \gamma - \gamma_w$
γ is the saturated unit weight of sediment
γ_w is the unit weight of seawater

Equation 5 can be rearranged to solve for the value of k required to cause undrained failure:

$$k = (\tan ø - 0.5 \sin 2\beta) / (\gamma / \gamma')\cos^2 \beta \qquad (6)$$

Equation 6 was used to calculate k for the range of slopes in the Bella Coola chute source areas, for the two values of ø = 27° and 28° (Fig. 4). A constant saturated unit weight of sediment of 1.60 Mgm^{-3} and a unit weight of seawater of 1.006 Mgm^{-3} (salinity of 30‰ and temperature of 10°C) were assumed. Recent seismic zoning maps (Basham, 1983) indicate that the peak horizontal earthquake acceleration (k) for the Bella Coola area is 0.11. Figure 4 shows that for ø = 28°, the maximum acceleration of k = 0.11 is required to cause failure on even the steepest slopes (β = 15°). For ø = 27°, the same value of k will cause failure on a slightly gentler slope (β = 14°) These results indicate that, acting alone, only the largest earthquakes are capable of producing undrained slope failure on the delta front slopes.

GAS GENERATION AND TIDAL DRAWDOWN

Rapid biochemical and bacterial action in organic matter in sediments results in the generation of gas. At saturation levels the gas enters the bubble phase and may act to increase pore pressures in the sediment (Esrig and Kirby, 1977). In areas affected by large tidal ranges, such as Bella Coola (3.9 m mean range, 5.9 m large range), excess pore pressures can be produced as the tide falls. If the sediment has a low permeability, the movement of water is retarded as the tide

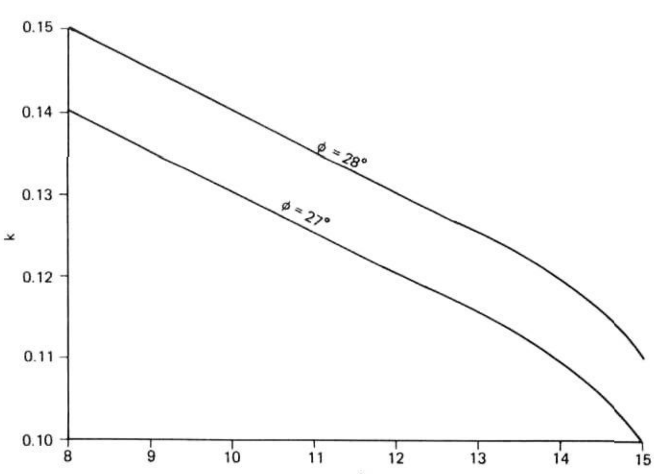

FIGURE 4. Values of earthquake acceleration, k, required to cause an undrained failure in sandy silt, versus bottom slope, β. Criteria are provided for the two values of total stress friction angle, ϕ, of 27° and 28°.

Valeurs d'accélération (k) d'un tremblement de terre nécessaires pour provoquer la rupture dans un matériel non drainé de silt sableux selon la pente inférieure (β). Calculs effectués pour des valeurs de l'angle de frottement de contrainte totale (ϕ) de 27° et 28°.

drops and excess pressures result (Terzaghi, 1956). We have no way of quantitatively assessing these effects in Bella Coola, but there is indirect evidence for excess pore pressures, possibly related to gas generation and/or tidal drawdown, on the upper delta front near the break in slope with the delta plain.

During extremely low tides, small sand volcanoes (Fig. 5) appear on the intertidal zone. The volcanoes represent a release of pressure from the sediment. The material discharged from the volcanoes is dark and organic rich and highly odorous, suggesting gas generation as a pressure-generating mechanism.

Excess pore pressures in this region were likely responsible for a slope failure that occurred during a period of extremely low tide and low river discharge in 1982. The failure took place at the steeply sloping (15°) seaward edge of a distributary mouth bar and was characterized by the rapid upward projection and subsequent submarine transport of a large log buried in the sediments. The tidal fall preceding the slide exceeded 5.7 m in less than four hours, suggesting that tidal drawdown may have been a contributing factor in slide initiation.

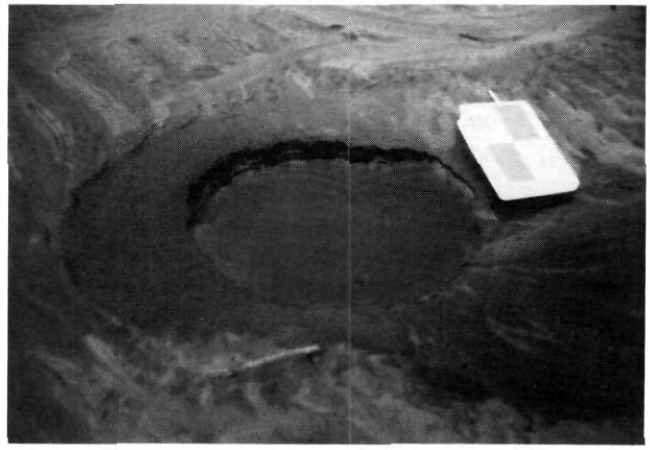

FIGURE 5. Sand volcanoe of the intertidal zone near the break in slope between delta plain and delta front. The note book is 20 cm in length.

Volcan de sable dans la zone intertidale près de la rupture de pente entre la plaine deltaïque et le front du delta. Le cahier mesure 20 cm de longueur.

DEPOSITIONAL LOADING

Rapid deposition of sediment increase pore water pressures in underlying sediments, thus reducing the strength of the material (Prior and Suhayda, 1981). Prior and Suhayda (1981) provide a method, based on infinite slope analysis and undrained loading, to estimate the decrease in the factor of safety for loaded sediments. The assumption of undrained loading implies that the sediment load is immediately transferred to a pore pressure increase and that there is no loss in pressure through drainage. After loading, the initial undrained factor of safety, F, is reduced to F_L:

$$F_L = F\,[(z/h) / (z/h + 1)] \qquad (7)$$

where: z is the distance to the failure plane
h is the thickness of the load

On the Bella Coola delta, depositional loading is likely of considerable importance in chute source areas near distributary mouths. As suggested above, the sandy silt deposits in these areas should have sufficiently low permeability to restrict drainage and, during rapid deposition, to approximate undrained conditions. Figure 6 shows values of z/h required to cause slope failure in Bella Coola ($F_L = 1$), versus bottom slope. Initial factors of safety (F) were calculated from Equation 3. As β increases z/h increases, and for a specific z, h decreases as slope increases.

In order to determine values of h at Bella Coola, repeat bathymetric surveys at distributary mouths, measured during high discharge periods, would be required. Such data are not available, but we can provide an approximation of h from the progradation rate of the delta. The only bathymetric chart of the delta was surveyed by the Canadian Hydrographic Service in 1956. A number of aerial photographs of the delta are available, but only one set, from 1964, were taken during sufficiently low discharge (low turbidity of river water) and low tidal conditions to permit identification of the break in slope between the subaerial delta plain and the subaqueous delta front. By comparing the 1956 chart and a 1964 aerial photograph (A18598-62) we found that the delta at the mouth of the North Channel had prograded 66 m seaward. This produces a progradation rate of 8.6 myr^{-1}, a value comparable to other fjord deltas such as the Squamish (Bell, 1975). Assuming a bottom slope of 15° for the chute source area at the distributary mouth, this would produce a maximum depositional load of h = 2.2 m. Most of this deposition would occur during the two month freshet period when fluvial bed material is in transit (Kostaschuk and McCann, 1983). For a bottom slope of 15°, z/h required for failure is 1.05 for ø = 28° and 1.10 for ø = 28° (Fig. 6). A load of 2.2 m would thus cause failures of z =

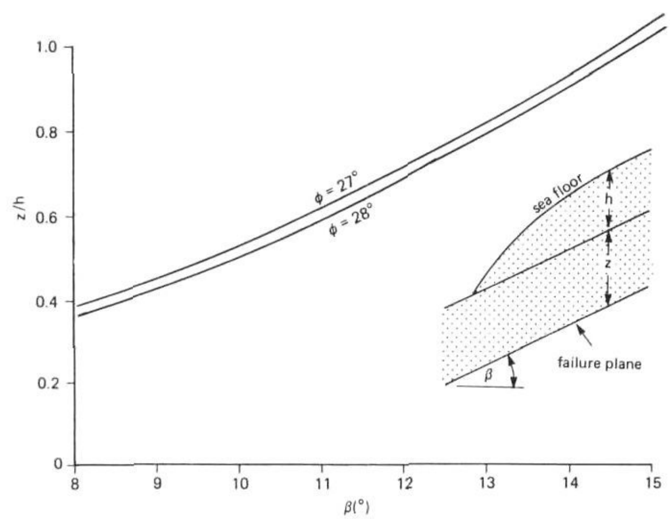

FIGURE 6. Depositional load thicknesses, h, expressed in relation to the depth to failure plane, z, required to cause undrained failure ($F_L = 1$) versus bottom slope β. Criteria are provided for $\phi = 27°$ and 28°.

Épaisseurs de la charge d'accumulation (h) exprimées en relation avec la profondeur du plan de rupture (z) nécessaire pour provoquer une rupture dans un matériel non drainé ($F_L = 1$) selon la pente inférieure (β). Calculs pour des valeurs $\phi = 27°$ and 28°.

2.3 m for $\phi = 28°$ and 2.4 m for $\phi = 27°$. The question remains whether deposition is rapid enough and pore pressure dissipation slow enough to cause undrained failure, but this analysis suggests that depositional loading alone is capable of causing shallow mass movements at distributary mouths.

WAVE LOADING

The passage of many waves in a storm over a slope generates cyclic shear stresses in the slope. These stresses create residual pore-water pressures which reflect the history of wave loading and the drainage characteristics of the sediment. If the pore pressures rise to the point where they equal the effective overburden pressure, the sediment loses its strength and liquefaction occurs. Pore pressures need not rise to the level required for full liquefaction for failure to occur, but to a level sufficient to allow failure to occur under gravitational stress (Luternauer and Finn, 1983).

Residual pore pressures and the potential for liquefaction of the sea bed by waves at Bella Coola have been estimated using a procedure outlined by Seed and Rahman (1978). The method involves reducing the complex pattern of waves in a storm to an equivalent storm of waves of the significant wave height and assumes undrained loading. True undrained loading is unlikely in granular sediment, but for an entire storm the errors introduced by this assumption are not significant (Seed and Rahman, 1978). The pore water pressure ratio, u_g/σ'_o at any depth (z) in the sediment is determined from (Seed and Rahman, 1978):

$$u_g/\sigma'_o = 2 / \pi \arcsin (N_c / N_l)^{1/2\theta} \quad (8)$$

where: u_g is the pore water pressure
σ'_o is the effective overburden pressure of the sediment
N_c is the number of cycles of the stress ratio τ_{av}/σ'_o generated by the storm
N_l is the number of cycles of τ_{av}/σ'_o required to cause liquefaction
θ is an empirical constant that reflects sediment character.

Liquefaction will occur when the pore pressure (u_g) equals or exceeds the effective overburden pressure of the sediment (σ'_o), that is when $u_g/\sigma'_o \geq 1$. The empirical constant θ represents the rate of pore pressure generation within the sediment and has a value of 0.7 for most sandy sediment (Seed and Rahman, 1978). Evaluation of θ directly requires geotechnical tests not available for Bella Coola and we have selected the value of 0.7 for our analyses. Seed and Rahman's procedure is lengthy and is outlined in some detail below.

The first step in assessing the wave induced liquefaction potential using Seed and Rahman's (1978) method is to reduce the waves in a 'design' storm to the equivalent storm of waves represented by the significant wave height. Design storms are commonly assumed to be 1 hour long (Luternauer and Finn, 1983). Observations by Kostaschuk and McCann (1983) indicate that waves generated by strong onshore winds in summer have a significant wave height (H) of 1.5 m, a length (L) of 25 m and a period (T) of 4 s. The wave content (H,T,L,N_w = number of waves) of a 1 hr. storm with these characteristics, using linear wave theory (Seed and Rahman, 1978), is shown on Table IIa.

The next step in Seed and Rahman's (1978) procedure is to calculate the stress ratio $\tau_{av}/\sigma'_o]_{z=o}$ at the top of the sea bed (z = o) for each wave height component in the design storm (Table IIa). The stress ratio represents the average cyclic shear stress generated by the waves (τ_{av}) relative to the overburden pressure of the sediment (σ_o') at the sea bed (z = 0). It is interesting to note that the overburden pressure at the sea bed is zero and as such the stress ratio is mathematically undefined. The form of the ratio at the sea bed is simply one of convenience for subsequent calculations of cyclic stresses beneath the sea floor. For Bella Coola, $\tau_{av}/\sigma'_o]_{z=o}$ was determined from a chart provided by Seed and Rahman (1978: Fig. 5). The chart utilizes ratios of d/L (d is water depth) and H/L as input for estimating $\tau_{av}/\sigma'_o]_{z=o}$. The value of d for each wave height was determined from H/d = 0.78, the position of maximum wave pressure (Luternauer and Finn, 1983). We then estimate the number of cycles of $\tau_{av}/\sigma'_o]_{z=o}$ required to cause liquefaction, N_l, using a second chart provided by Seed and Rahman (1978: Fig. 12) and a value of $\theta = 0.7$. The number of cycles of $\tau_{av}/\sigma'_o]_{z=o}$ generated by each wave component of the storm, N_{ci} is then computed from (Table IIb):

TABLE IIa

Wave loading at the sea floor in Bella Coola

H(m)	T(s)	L(m)	N_w	$\tau_{av}/\sigma'_o]_{z=o}$	N_l	N_{ci}
1.69	4.3	27.5	81	0.24	1.8	259
1.50	4.0	25.00	130	0.22	2.4	312
1.13	3.7	22.82	252	0.18	7.0	206
0.75	3.1	16.75	293	0.14	14.8	115
0.38	2.5	13.83	325	0.08	0	0
					$N_c = \Sigma N_{ci}$ =	892

Values of wave height (H), period (T), length (L) and number of waves (N_w) represent the wave content in a 1 hr design storm. $\tau_{av}/\sigma'_o]_{z=o}$ is the cyclic stress ratio, N_l is the number of cycles of τ_{av}/σ'_o required to cause liquefaction and N_{ci} and N_c are the number of cycles of τ_{av}/σ'_o generated by each wave component and the entire storm, respectively.

TABLE IIb

Pore pressure generation beneath the sea floor in Bella Coola

z(m)	z/L	f_z	τ_{av}/σ'_o	N_l	u_g/σ'_o
0	0	1.00	0.22	2.4	1
1	0.04	0.79	0.17	4.2	1
2	0.08	0.62	0.14	12	1
3	0.12	0.48	0.11	80	1
4	0.16	0.39	0.08	9,500	0.17
5	0.20	0.30	0.06	100,000	0.01

Z is the distance below the bed, f_z is stress reduction factor and u_g/σ'_o *is the pore pressure ratio.*

$$N_{ci} = (N_w / N_l)\, N_{ref} \quad (9)$$

where: N_{ref} is the number of cycles of $\tau_{av}/\sigma'_o]_{z=o}$ required for liquefaction by the significant wave.

For Bella Coola the significant wave for the design storm is H = 1.5, thus N_{ref} = 2.4 (Table IIa). The value of N_c is the sum of the N_{ci} values, N_c = 892 (Table IIa).

Pore pressures within the sediment beneath the bed vary with the relative density (D_r) of the sediment, the cyclic stress ratio (τ_{av}/σ'_o) and the existing pore pressure (Seed and Rahman, 1978). For the Bella Coola analysis, we are assuming a density ratio of D_r = 0.5 and that the existing pore pressure is hydrostatic. We have computed the values of $\tau_{av}/\sigma'_o]_{z=o}$ at the sea bed and must estimate values of τ_{av}/σ'_o at depths (z) below the sea floor, for the significant wave (Seed and Rahman, 1978). The significant wave in Bella Coola (H = 1.5 m: Table II) has a value of $\tau_{av}/\sigma'_o]_{z=o}$ of 0.22 at the bed, and this decreases with sediment depth below the sea floor. The reduction in τ_{av}/σ'_o can be predicted using a depth reduction factor (f_z) chart provided by Seed and Rahman (1978: Fig. 6). The depth reduction factor is based on the relationship between sediment depth (z) wave length (L) and θ (Table IIb). For Bella Coola, we used values of z from 0 to 5 m and L of 25 m to predict τ_{av}/σ'_o (Table IIb). Values of N_l below the sea floor were then determined from the Seed and Rahman (1978: Fig. 12) chart in the same manner as for $\tau_{av}/\sigma'_o]_{z=o}$. Finally, values for u_g/σ'_o for z = 0 to 5 m were computed using Equation 8, N_c = 892 (Table IIa) and N_l from Table IIb. The results show that u_g/σ'_o exceeds 1 to a sediment depth of approximately 3 m, indicating that the 1 hr design storm at Bella Coola could result in shallow sediment liquefaction in chute source areas.

DISCUSSION

The stability analyses applied to the Bella Coola Delta are based on a large number of simplifying assumptions, some of which have been discussed earlier. In addition, the geotechnical and environmental data which serve as the input for these procedures are not extensive. In spite of these limitations, such analyses are useful in providing an indication of the role individual factors may play in initiating mass movements on the delta. Failure thresholds, however, usually result from a complex interaction of variables rather than a single cause and the most unstable areas are those where a number of factors are important (Prior and Coleman, 1983).

The stability analyses indicate that earthquakes, depositional loading and wave loading are capable of producing slides in chute source areas. We are unable to quantify the effects of gas generation and tidal drawdown, but both of these probably reduce sediment strength by increasing pore pressures, thereby increasing the opportunity for failures generated by other mechanisms. Slope failures produced by slope oversteepening alone would require much steeper slopes than existed at the time of measurement, but depositional loading would be acting simultaneously with slope oversteepening, reducing the slope angle required for failure by gravitational stresses alone. The most unstable chute source areas are those at distributary mouths where all of the mechanisms of failure generation could be operating at once.

Most of the causes of mass movements on submarine slopes of the delta front would result in relatively low magnitude, high frequency failure. Slope oversteepening and depositional loading will be important during periods of high river discharge. High flows occur annually in spring and less frequently during fall and early winter floods. These effects will be localized, produced failures at distributary mouths. Large tidal ranges, and the potential for tidally-induced failures, will occur for 4 or 5 days per month during spring tides and will effect all chute source areas. Failures produced by waves will take place in summer when winds are directed onshore. Gas generation is probably an important source of instability in all areas of the delta but it is impossible to speculate on its temporal variability. The most important high magnitude, low frequency, potential cause of mass movements is earthquakes. There is a 10 % probability that an earthquake with peak accelerations greater than k = 0.11 will occur over a 50 year period in Bella Coola (Basham, 1983). Thus, earthquakes could be important in producing infrequent but large-scale movement on the upper delta front, although there is no morphologic evidence such as that found on the Kitimat Delta (Prior *et al.*, 1983), for this. In addition, the earthquake stability analysis indicates that additional factors, such as gas generation, would be required for failure on all but the steepest slopes. The above considerations indicate that low magnitude, high frequency mass movements originating in chute source areas are most likely to occur in spring and summer, and that high magnitude, earthquake-induced failures are probably very infrequent.

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REFERENCES

Almagor, G. and Wiseman, G., 1982. Submarine slumping and mass movements on the continental slope of Israel, p. 95-128. *In* S. Saxov and J. K. Nieuwenhuis, ed., Marine Slides and other Mass Movements. Plenum Press, New York, 353 p.

Basham, P. W., 1983. New seismic zoning maps for Canada. Geos, 72: 10-12.

Bell, L. M., 1975. Factors influencing the sedimentary environments of the Squamish river delta in southwestern British Columbia. Unpublished MASc thesis, University of British Columbia, Vancouver, B.C.

Cook Pickering and Doyle, 1977. Geotechnical investigation for wharf replacement and associated works, Bella Coola, B.C. Cook, Pickering and Doyle Ltd., Vancouver, B.C.

——— 1982. Geotechnical investigation for wharf replacement and associated works, Bella Coola, B.C.. Cook, Pickering and Doyle Ltd., Vancouver, B.C.

Esrig, M. I. and Kirby, R. C., 1977. Implications of gas content for prediction of stability of submarine slopes. Marine Geotechnology, 2: 753-766.

Folk, R., 1974. Petrology of Sedimentary Rocks. Hemphills, Austin, Texas, 170 p.

Hart, J. S., 1981. The physical environment of the Bella Coola Valley. Hart-Mayal Consultants, Tatla Lake, B.C., 46 p.

Hunt, R. E., 1984. Geotechnical Engineering Investigation Manual. McGraw-Hill Book Company, New York., 983 p.

Johns, M. W., Prior, B. D., Bornhold, D. B., Coleman, J. M. and Bryant, W. R., 1986. Geotechnical aspects of a submarine slope failure, Kitimat Fjord, British Columbia. Marine Geotechnology, 6: 243-251.

Karlsrud, K. and Edgers, L., 1982. Some aspects of submarine slope stability, p. 61-81. *In* S. Saxov and J. K. Nieuwenhuis, ed., Marine Slides and Other Mass Movements. Plenum Press, New York, 353 p.

Kostaschuk, R. A. and McCann, S. B., 1983. Observations on delta-forming processes in a fjord-delta, Bella Coola, British Columbia, Canada. Sedimentary Geology, 36: 269-288.

——— S. B., 1987. Subaqueous morphology and slope processes in a fjord-delta, Bella Coola, British Columbia. Canadian Journal of Earth Sciences, 24: 52-59.

Luternauer, J. L. and Finn, W. D. L., 1983. Stability of the Fraser River delta front. Canadian Geotechnical Journal, 20: 603-616.

Morgenstern, N. R., 1967. Submarine slumping and the initiation of turbidity currents, p. 113-155. *In* A. F. Richards, ed., Marine Geotechnique. University of Illinois Press.

Prior, D. B. and Suhayda, J. N., 1981. Application of infinite slope analysis to subaqueous slope stability, p. 5-76 to 5-93. *In* H. A. Bouma, ed., Offshore Geologic Hazards, A. A. P. G. Education Course Note Series No. 18.

Prior, D. B. and Coleman, J. M., 1983. Lateral movements of sediments. Ocean Science and Engineering, 8: 113-155.

Prior, D. B., Coleman J. M. and Bornhold, B. D., 1983. Results of a known sea floor instability event. Geomarine Letters, 2: 117-122.

Seed, H. B. and Rahman, M. S., 1978. Wave-induced pore pressure in relation to ocean floor stability of cohesionless soils. Marine Geotechnology, 3: 123-150.

Selby, M. J., 1982. Hillslope Materials and Processes. Oxford University *Press, Oxford, 264 p.*

Skempton, A. W. and DeLory, F. A., 1952. Stability of natural slopes in London Clay, p. 378-381. *In* Proceedings of the 4th International Conference on Soil Mechanics and Foundation Engineering, London, 2.

Terzaghi, K., 1956. Varieties of submarine slope failure, p. 1-41. *In* 8th Texas Oil Mechanical and Engineering Conference. Houston, Texas.

Western Canada Hydraulics, 1976. Potential sediment problem in the Bella Coola small boat harbour. Western Canada Hydraulics Laboratory, Port Coquitlam, B.C., 2 p.