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Effect of Erosion on the Hydrogeological Behaviour of Badland Surfaces in Western Canada

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ABSTRACT: Climatic conditions and in situ lithology govern the hydrogeological behaviour of badland surfaces in western Canada. Based on field observations, samples representing three distinct surfaces in the Avonlea badlands (60 km SSW of Regina) of Saskatchewan were collected. The influence of erosion on the engineering properties of this typical indigenous badland profile was investigated by measuring the grain size distribution (GSD) using dry sieving and wet sieving along with hydrometer analysis and estimating the soil water characteristic curves (SWCC) from the two sets of laboratory data. Results indicated that the various selected sediments respond differently to the same weather changes and that the angle of repose slopes at the site closely correspond to possible erosion patterns. Based on an increase in fines (material finer than 0.075 mm), grain size thinning was found to be highest in weathered mudrock (75%) followed by basal pediment (32%) and then by cemented sandstone (16%). The estimated air entry values (AEV) corresponding to dry sieving and wet sieving plus hydrometer analysis followed the same trend: 0.6 kPa and 2340 kPa; 1.6 kPa and 7 kPa; and 1.6 kPa and 1.6 kPa for the three materials, respectively.

1 Introduction

The determination of unsaturated soil properties is of pivotal importance for construction in arid and semi-arid regions of the world. Western Canada is characterized by wide variation in precipitation and temperature when comparing the summer season to the winter. According to Environment Canada, the average monthly rainfall in southern Saskatchewan measures 15 ± 5 mm over October–March and reaches a maximum of 70 mm in June–July. The average temperature for the same area and the same winter months ranges from –15 ^{o}C to 0 ^{o}C and can be as high as 20 ^{o}C during summer. Such harsh climatic conditions influence the geological evolution and engineering behaviour of all types of sediments in the area (Hayashi et al. 2003). Poorly consolidated and loosely bonded materials are particularly affected because of their erosion susceptibility. Bryan and Yair (1982) reported erosion rates of up to 18 mm/yr in badlands resulting from several interrelated factors such as rain splash, overland flow, sheet wash, concentrated flow, pipe flow, and mass movement. The combined impact of these erosion processes results in a complex hydrogeological behaviour of badlands (Kasanin-Grubin and Bryan 2007).

Badlands are areas of little agricultural value and show a variety of forms reflecting the contrasting lithologies and the governing slope forming processes such as erosion and weathering. These landscapes generally exhibit a high drainage, V-shaped valleys, and mild to steeper slopes (Archibold et al. 2003). Figure 1 gives the typical profile of badlands in western Canada as identified by Campbell (1989). The profile has three distinct surfaces, namely; an upper slope with cemented sandstone, a mid-slope formed in mudrock with a weathered popcorn surface, and a basal pediment surface. The steepest slopes are developed in slightly cemented materials with localised iron-rich outcrops. The sandstone lithology is such that drainage in this zone is often routed through a deep pipe network that can trigger mass movement along tensional cracks and fissures (Hardenbicker and Crozier 2002). The mid-slopes containing clayey materials are quite responsive to changes in rainstorm patterns and surface sealing upon wetting can be profound. Swelling and shrinking due to moisture changes in this zone can cause the functional drainage network to change considerably between different storms, for example, the hydrated clays can cut off many desiccation cracks thereby affecting bypass flow (Faulkner et al. 2003). The absence of shrinkage cracks in the alluvial surface translates to a low infiltration that generates a near uniform sheet flow over the basal pediment for most rainfalls (Howard 1994). In summary, the three distinct surfaces respond differently to the same precipitation events thereby affecting the shear strength and volume change properties to variable extents. The determination of unsaturated soil properties requires a clear understanding of the hydrogeological behaviour of local badlands.

The main objective of this paper was to investigate the hydrogeological behaviour of Avonlea badlands (60 km SSW of Regina) in Saskatchewan. Initially, field observations were analyzed to assess the in situ geomorphology and to select soil samples representing the three distinct surfaces in local badlands. Then, the influence of erosion on the engineering properties of the typical western Canadian badland profile was investigated. For this purpose, the GSD was measured using dry sieving and wet sieving along with hydrometer analysis. Finally, the SWCC were estimated from the two sets of laboratory GSD data.

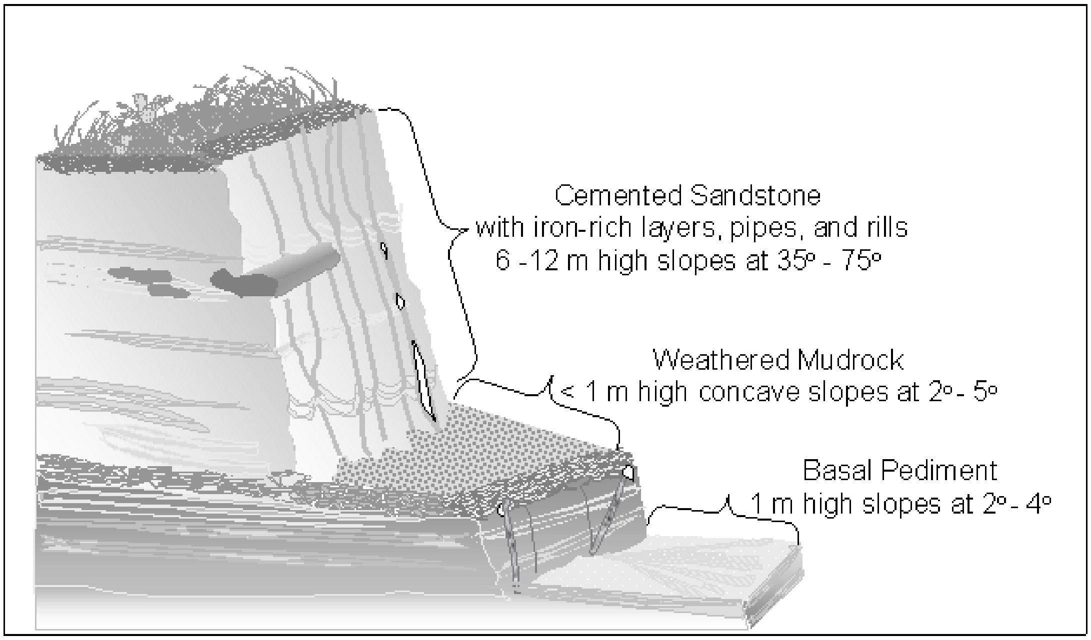

Figure 1: Typical badland profile in western Canada

2 Field observations

The study site in the Avonlea region (60 km SSW of Regina) of Saskatchewan is part of the Eastend Formation. This formation consists of an upper unit (generally with thick-bedded sandy strata forming a steep slope) and a lower unit (with a thin-bedded muddy strata capped by a bentonitic layer). The development of the investigated badlands was triggered by rapid post-Pleistocene incision of a meltwater channel in the marine and lagoonal sediments of the Upper Cretaceous. These sediments generally comprised of unconsolidated and weakly cemented materials such as silty clays, shales, and marls (Hodges and Bryan 1982). Alterations of climate over geologic time imparted significant changes in the badland development in situ. Figure 2 describes the salient features of the three distinct layers in the Avonlea badlands: (a) cemented sandstone, (b) weathered mudrock, and (c) basal pediment.

2.1 Cemented sandstone

The cemented sandstone had a light grey colour (dry 10YR-3/2) and created the upper steep slopes as given in Figure 1. According to Kent and Vigrass (1973), this layer of the investigated badlands is primarily composed of quartz and calcite sand grains with resistant concretionary ironstone fragments. Overall, the sandstone included cross-bedded arkoses and thin silty shale sheets with dense rills and pipes. The sandstone surface was found to have a very thin weathering rind that was frequently pitted due to raindrop impacts. At the site, an ironstone layer forming a distinct step in the middle of the profile bisected the slope profile. Rills in the lower part of the profile were observed to be 35 cm to 40 cm apart (Imeson and Verstraten 1988).

2.2 Weathered mudrock

The mudrock had a dark olive grey colour (dry 5 Y-5/2) and was found to possess a maximum of 50 cm deep weathered surface crust. The “popcorn” layer comprised of loosely connected crumbs (up to 10 mm in size) formed by desiccation of an initially water bearing clayey material. Due to surface sealing upon wetting, this layer protects the underlying layer from most climatic events. Consequently, the bottom intact layer was observed to be relatively lighter in colour (minimal physical and chemical weathering) and contained old angular shards.

2.3 Basal pediment

The basal pediment had a light grey colour (dry 10YR 4/3) and showed no evidence of clayey materials. Although, traces of air bubbles (up to 2 mm in size) could be seen beneath the surface, the absence of desiccation cracks in the alluvial deposit indicated the dominance of sheet flow on the surface.

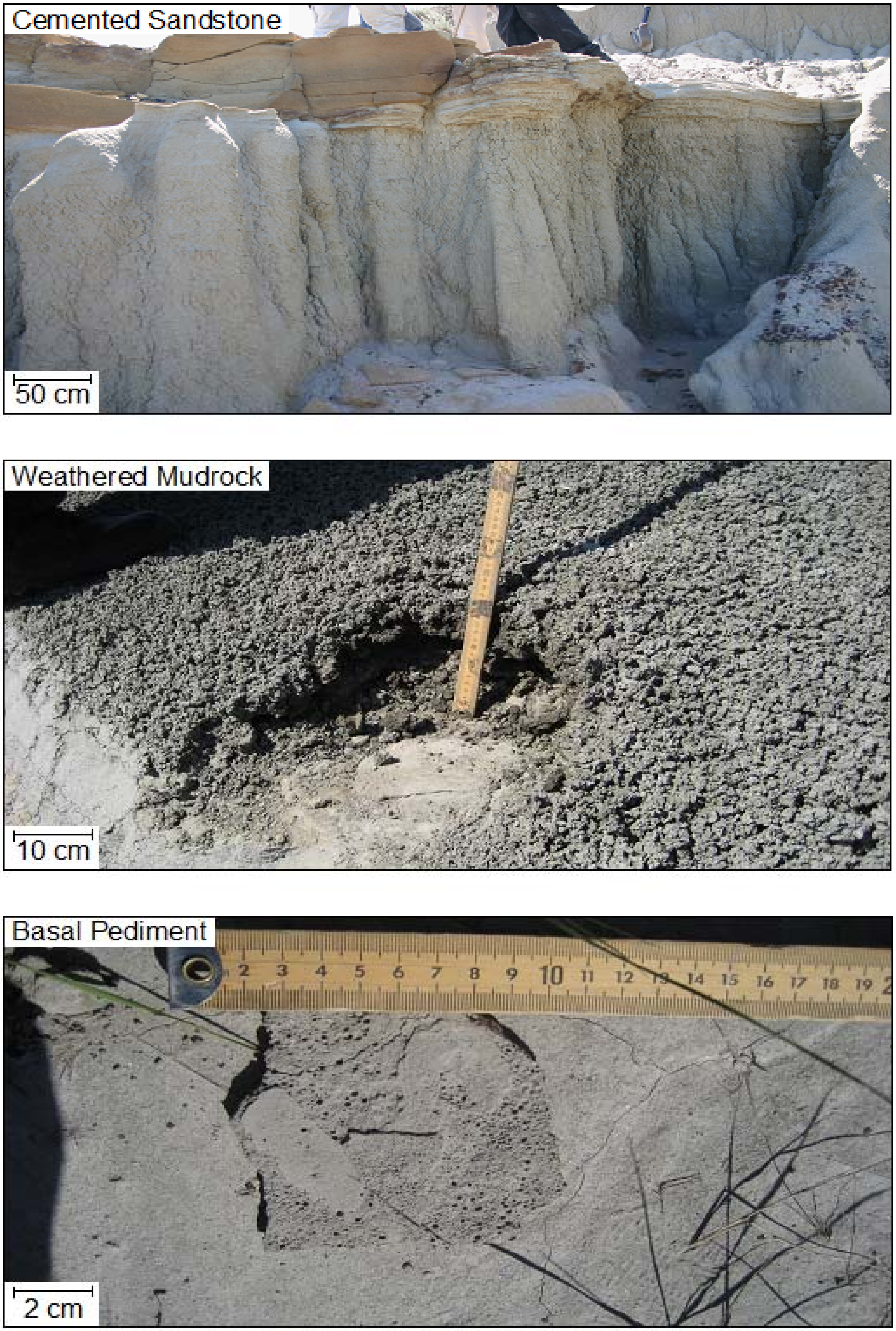

Figure 2: Various distinct layers in the Avonlea badlands

3 Investigation methods

Representative soil samples were retrieved from the above-mentioned three distinct surfaces of Avonlea badlands. The geotechnical index properties including gravimetric water content (w), specific gravity (G_s), and dry unit weight (γ_d) were determined according to the following ASTM procedures: Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (D 2216-05), Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (D 854-06), and Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method (D 2937-04), respectively. The gravimetric water content was converted to the volumetric water content by multiplying the former with γ_d and assuming that the unit weight of water equals 1.0 g/cm^3. The GSD was measured in the laboratory in three stages: (i) dry sieving (according to ASTM D 6913, with the modification that air-dried samples were used instead of oven dried samples to preserve the grain sizes representative of the field); (ii) wet sieving (using distilled water to simulate the effect of precipitation on grain size distribution); and (iii) hydrometer analyses on material finer than 0.075 mm (in accordance with the ASTM D 422-63(1998) standard test method to determine the actual grain sizes of the fines). Material coarser than 0.075 mm was defined as sand and that finer than 0.075 mm was defined as fines. Likewise, the percentage of grain size less than 0.002 mm was defined as clays. Further, the fines included both silts (material ranging between 0.075 mm and 0.002 mm) and clay. The measured GSD data were fitted according to the following unimodal equation (Fredlund et al., 2000):

$$P_p(d) = \frac{1}{\ln\left[\exp(1) + \left(\frac{g_a}{d}\right)^{g_n}\right]^{g_m}} \left[1 - \left[\frac{\ln\left(1 + \frac{d_r}{d}\right)}{\ln\left(1 + \frac{d_r}{d_m}\right)}\right]^7\right] \quad (1)$$

where:

$P_p(d)$ = percent passing a particular grain-size, d,
g_a = fitting parameter corresponding to the initial break in the grain-size curve,
g_n = fitting parameter corresponding to the maximum slope of grain-size curve,
g_m = fitting parameter corresponding to the curvature of the grain-size curve,
d = grain diameter (mm),
d_r = residual grain diameter (mm),
d_m = minimum grain diameter (mm)

The mathematical fit equation describing the measured GSD data along with the geotechnical index properties (w, G_s, and γ_d) were used to estimate the SWCC in the computer software of SoilVision Systems. Based on a physico-empirical approach, the software divided the GSD into uniform particle sizes, each size assigned an individual SWCC from the database of measured SWCC, and all summed to develop the entire curve (Fredlund et al., 2002). To confirm the mathematical predictions, part of the SWCC during desorption was determined for basal pediment. A pressure plate (156 mm internal diameter and 178 mm high) along with a high air-entry ceramic disk was used. The test was conducted as per the ASTM Standard Test Method for Capillary Moisture Relationships for Coarse and Medium Textured Soils by Porous Plate Apparatus (D 2325-68(2000)).

4 Result and discussion

Table 1 summarizes the geotechnical index properties and the GSD analyses for the three surface samples of Avonlea badlands. The G_s of the various samples measured 2.80 ± 0.05 and the individual values mathced material composition. The γ_d values showed variation and were indicative of field conditions at the study site.

The GSD is a continuous curve representing the amount of various grain sizes present in a soil. Figure 3 gives the measured GSD data using dry sieving and wet sieving plus hydrometer analysis for the investigated samples as well as the fitted curves for the same using equation (1). The figure indicates that the unimodal curves matched reasonably well with the measured data. The material fraction finer than 4.75 mm was used along with the coefficient of curvature (C_c) and the coefficient of uniformity (C_u) to classify the various soils according to the Unified Soil Classification System (USCS). Samples containing more than 50% material finer than 0.075 mm were defined as fine-grained soils for which consistency limits reported by Hardenbicker et al. (2007) were used as part of the classification. Among the coarse-grained soils (containing 50% material coarser than 0.075 mm), well-graded soils exhibited a C_c between 1 and 3 together with a C_u of more than 6 for sands. Table 1 reveals that the increase in the amount of fines (material finer than 0.075 mm) was highest in weathered mudrock (75.1%) followed by basal pediment (31.7%) and then by cemented sandstone (16.3%). The variable grain size thinning of the investigated soils explains their variable erosion susceptibility during rainfall and corroborates field observations (Regues and Gallart 2004). The similar increase in clay size between the two test methods is attributed to particle breakage in the presence of water and dispersing agent and is expected to reduce erosion.

Table 1: Summary of geotechnical index properties and GSD analyses for the investigated samples

Sample identification and GSD test method	w (%)	G_s	γ_d (g/cm^3)	- 0.075 mm (%)	- 0.002 mm (%)	C_c*	C_u†	USCS classification
Cemented Sandstone (dry sieve)	2.8	2.78	1.74	6.3	0.2	1.1	2.2	SP-SM
Cemented Sandstone (wet sieve + hydrometer)				22.6	8.0	5.0	16.5	SM
Weathered Mudrock (dry sieve)	30.9	2.85	0.92	9.3	3.8	3.0	15.5	SW-SM
Weathered Mudrock (wet sieve + hydrometer)				84.4	38.4	------	------	MH
Basal Pediment (dry sieve)	2.7	2.76	1.33	28.8	0.0	0.9	2.5	SM
Basal Pediment (wet sieve + hydrometer)				60.5	6.4	2.6	11.0	ML

† Coefficient of Uniformity, $C_u = D_{60}/D_{10}$
* Coefficient of Curvature, $C_c = (D_{30})^2/(D_{10} \times D_{60})$

The soil water characteristic curve is primarily a representation of the pore sizes present in the soil. Figure 4 gives the predicted SWCC of the selected Avonlea badland samples and the results summarized in Table 2. The data depicted herein indicates different types of hydrogeological behaviour for the investigated materials and generally confirms the GSD data and field observations.

Table 2 Summary of the estimated SWCC for the investigated samples

Sample identification and GSD test method	Saturated volumetric water content	Air entry value (kPa)	Residual volumetric water content	Residual matric suction (kPa)
Cemented Sandstone (dry sieve)	0.37	1.6	0.10	11.0
Cemented Sandstone (wet sieve + hydrometer)	0.37	1.6	0.13	11.0
Weathered Mudrock (dry sieve)	0.68	0.6	0.16	2.5
Weathered Mudrock (wet sieve + hydrometer)	0.68	2340.0	0.07	229087.0
Basal Pediment (dry sieve)	0.52	1.6	0.15	47.9
Basal Pediment (wet sieve + hydrometer)	0.52	7.0	0.40	208.9

The cemented sandstone did not show any significant change in the various parameters obtained from the two SWCCs despite some grain size thinning. The identical AEV of 1.6 kPa (corresponding to 0.16 m of water) indicates that the clay size material minimizes possible erosion of the coarser particles. Some surficial erosion is still observable in the form of rain pitting on the slopes in the field, as shown in Figure 2. Overall, this predominantly sandy soil possesses enough friction along with the necessary cementation (provided by about 8% clay size fraction) to hold up to 12 m high steep slopes on the site (Azam et al. 2007). The nature of the cementing material should be investigated by determining the mineralogical composition of the clay size fraction. Furthermore, the low AEV of the cemented sandstone indicates that contribution from the suction component of shear strength is negligible for this material.

The low AEV of 0.6 kPa for the weathered mudrock (based on dry sieve GSD fit) is attributed to the highly porous nature of this soil in desiccated conditions, as shown in Figure 2. These pores were completely sealed when the clay size material (38%) adsorbed water upon wetting (precipitation or snow melt) thereby resulting in a high AEV of 2340 kPa. This is in accordance with GSD data that showed a change from an SW-SM (sand) to an MH (inorganic silt of high plasticity) material due to wetting. The high grain size thinning determined for this material (given in Figure 3) is not associated with erosion but instead with closing down of the pore spaces between the loosely connected popcorns (Bryan et al. 1984). This confirms the field observation of an intact bottom layer protected from climatic events by the overlying popcorn layer of the weathered mudrock.

The AEV of 1.6 kPa (based on dry sieve GSD fit) for the basal pediment was found to be similar to that for the cemented sandstone. This value increased to 7 kPa (based on wet sieve and hydrometer GSD fit) owing to sediment erosion as observed in the field. The measured data between 30 kPa and 500 kPa closely matched the predicted SWCC. The GSD fit (based on wet sieve and hydrometer) overestimated the clay size fraction as the actual measured data indicated less than 2% clay. Such a low amount of clay size cannot result in any appreciable reduction in erosion even in the presence of some active clay minerals (Mitchell and Soga 2005).

It is interesting to note that the cemented sandstone under wet conditions is identical to the basal pediment under dry conditions in the sense that both of the materials are classified as SM (silty sand) and have an AEV of 1.6 kPa. This suggests that the two surface sediments are genetically connected, that is, material erosion due to rainfall from the former (at a higher elevation) is accumulated in the latter (at a lower elevation) as observed during dry conditions. None of the eroded material is retained in the intermediate zone because the weathered mudrock behaves like a completely sealed surface. Since the basal pediment is relatively more susceptible to erosion than the other materials, it is converted to an ML (inorganic silt) material with a corresponding increase in AEV to 7 kPa during the wet season.

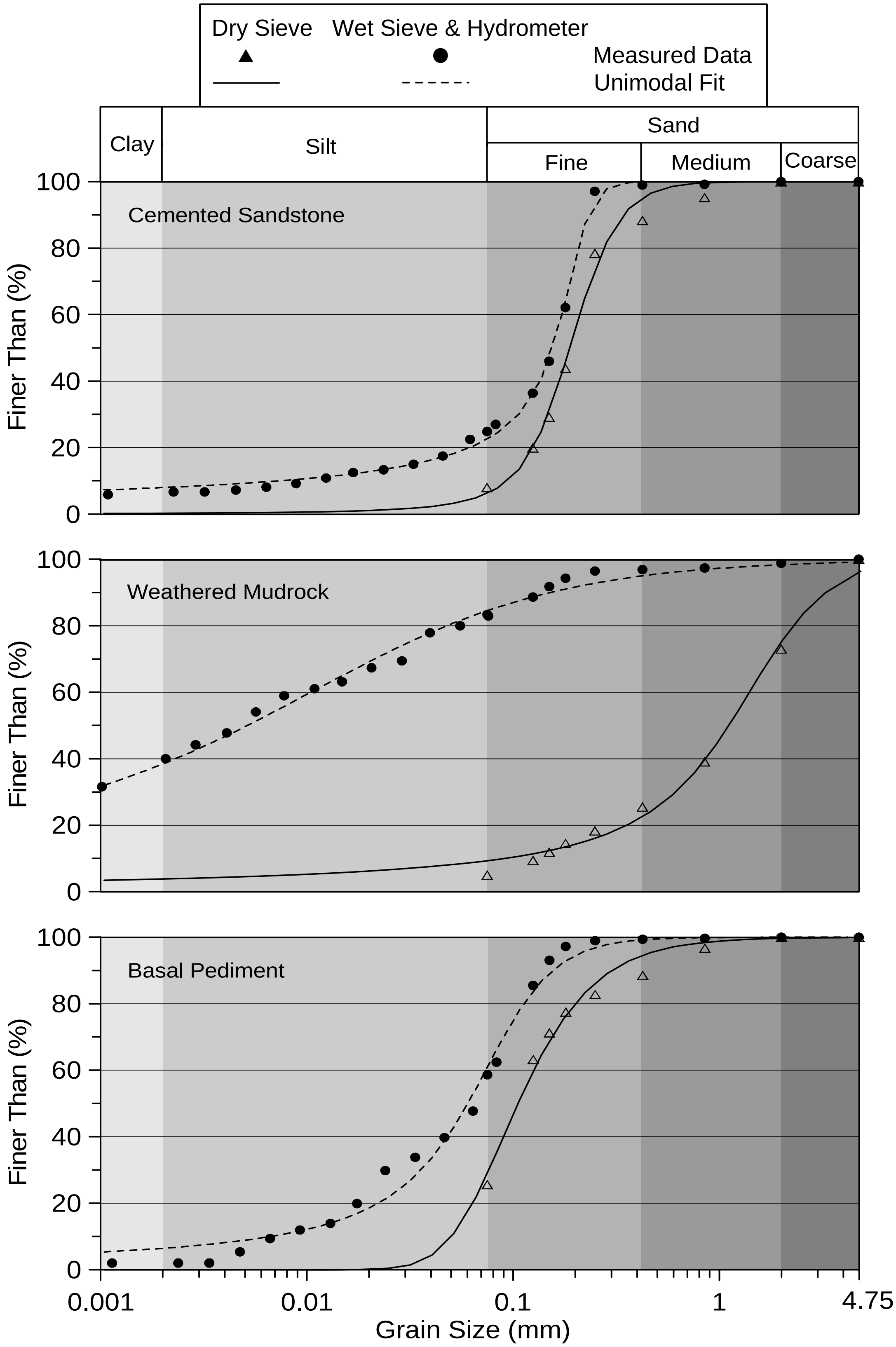

Figure 3: Grain size distribution for the selected samples

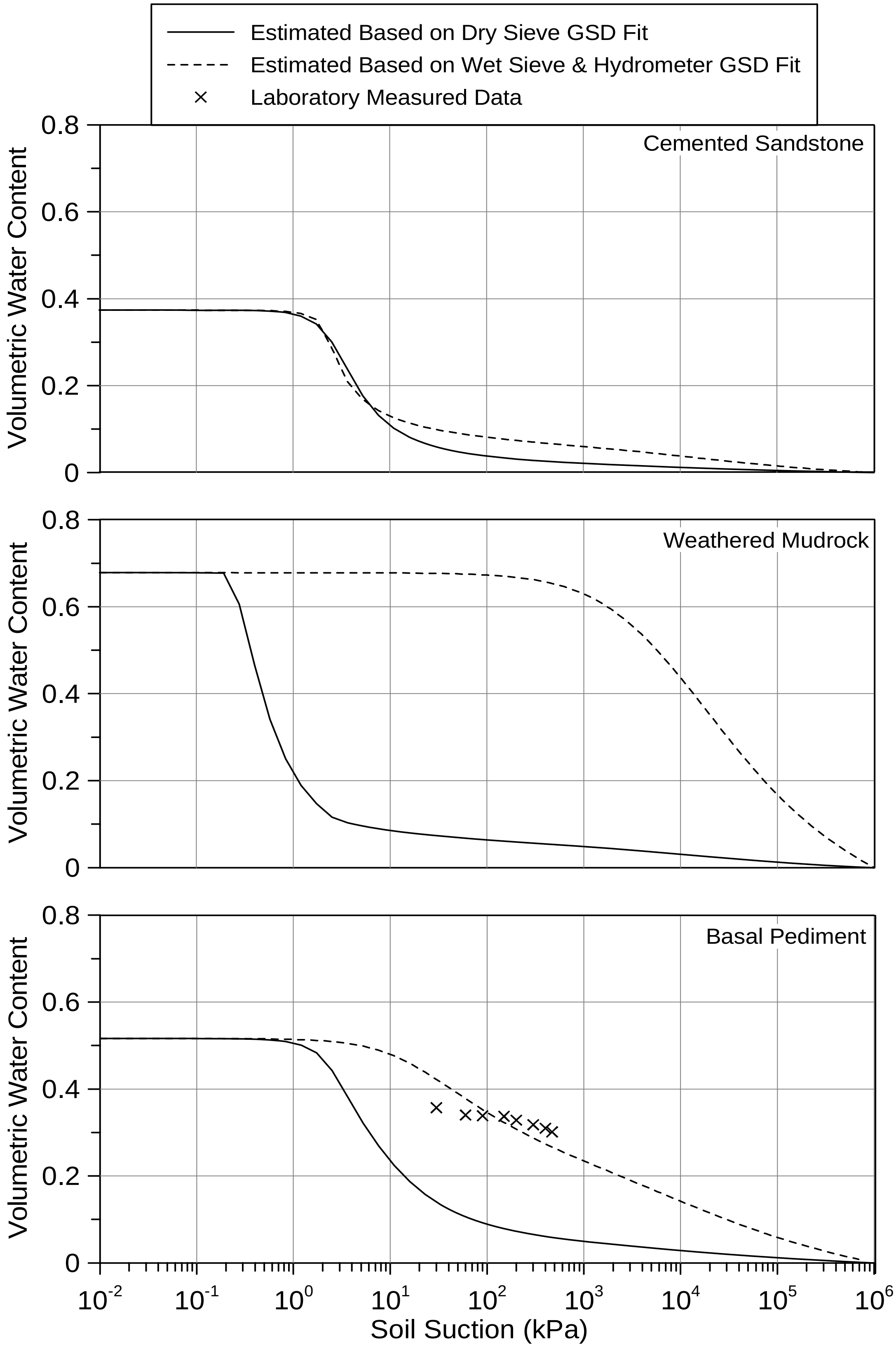

Figure 4: Soil water characteristic curves for the selected samples

5 Summary and conclusion

Field observations, laboratory investigations, and numerical modelling were conducted for selected samples representing three distinct surfaces in the Avonlea badlands (60 km SSW of Regina) of Saskatchewan. A general increase in fines content (material finer than 0.075 mm) was observed for all of the materials. Grain size thinning was found to be highest in weathered mudrock (75%) followed by basal pediment (32%) and then by cemented sandstone (16%). The estimated AEV corresponding to dry sieving and wet sieving plus hydrometer analysis followed the same trend: 0.6 kPa and 2340 kPa; 1.6 kPa and 7 kPa; and 1.6 kPa and 1.6 kPa for the three materials, respectively. Based on possible erosion patterns, the cemented sandstone was found to be genetically connected with the basal pediment. Future investigations are designed to focus on the determination of soil mineralogy, the confirmation of the SWCC in the laboratory, and the determination of hydraulic conductivity functions for the investigated materials.

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