

Effect of precipitation on the geological development of badlands in arid regions

Peter Imumorin · Shahid Azam

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Abstract The main objective of this paper was to study the effect of precipitation on the geological development of badlands in arid regions. Field observations and laboratory investigations were carried out to characterize the surface soils of the Avonlea badlands in southern Saskatchewan, Canada, which is currently experiencing a rapid development in infrastructure. Three distinct surface sediments were identified: an upper slope of cemented sandstone, a mid-slope on weathered mudrock and a relatively flat basal pediment. Each of these soils reacts differently to rainfall events. Precipitation results in grain size reduction which, together with the consistency limits, explains the water sensitivity of the soils; the fines increased by 16% in the cemented sandstone, 78% in the weathered mudrock and 33% in the basal pediment. Erosion susceptibility was highest in the basal pediment (2% clays) followed by cemented sandstone (cementation by 6% active clays) and then by weathered mudrock (cohesion due to the 40% clay).

Keywords Climate · Avonlea · Slopes · Badlands · Consistency limit · Desiccation

Résumé Le principal objectif de cet article a été d'étudier les effets des précipitations sur le développement du ravinement et la formation des badlands dans les régions de

climat aride. Des observations de terrain et des travaux de laboratoire ont été réalisés afin de caractériser les sols superficiels des badlands d'Avonlea, dans le sud-ouest du Saskatchewan au Canada, région qui connaît actuellement un important développement d'infrastructures. Trois différents matériaux de surface ont été identifiés : un grès cimenté de haut de pente, une argilite de milieu de pente et un dépôt de pédiment de bas de pente. Chacun de ces sols réagit différemment aux événements pluviométriques. Les précipitations ont pour conséquence une diminution de la taille des particules, ce qui, avec les indices de consistance, explique la sensibilité des sols à l'eau. Les particules fines augmentent de 16% dans les grès cimentés, de 78% dans les argilites altérées et de 33% dans les sédiments de pédiment. La sensibilité à l'érosion était plus élevée dans les sédiments de pédiment (avec 2% d'argiles) suivis par les grès cimentés (cimentés par 6% d'argiles actives) puis par les argilites altérées (présentant une cohésion du fait d'un pourcentage de 40% d'argiles).

Mots clés Climat · Avonlea · Pentes · Badlands · Consistance · Dessiccation

Introduction

Badlands are commonly found in arid and semi arid regions where materials are transported by fluvial erosion. According to Bryan and Yair (1982), the geomorphic activity in such deposits is primarily associated with seasonal climatic variations. In sub-tropical Mediterranean areas, erosion occurs due to high intensity rainfalls in winter whereas soils desiccate during the hot and dry summer (Regues and Gallart 2004). Conversely, surface soils are covered with snow during the cold winters

P. Imumorin
SaskEnergy TransGas, SaskEnergy Place,
1777 Victoria Ave., Regina, SK S4P 4K5, Canada

S. Azam (✉)
Environmental Systems Engineering,
Faculty of Engineering and Applied Science,
University of Regina, 3737 Wascana Parkway,
Regina, SK S4S 0A2, Canada
e-mail: Shahid.Azam@uregina.ca

prevalent in high latitude continental areas, and physical material weathering is triggered by subsequent snowmelt and intermittent precipitation in summer. The resulting terrains in both types of environment are characterized by rills and gullies in steep cemented sandstone rising above pediment materials with intervening mudrock slopes (Warren 1984). Overall, the distinct landform features closely reflect lithological variations and the different erosion resistance of the various materials.

The town of Avonlea is located at latitude 50.0367 and longitude 105.0667 in southern Saskatchewan, Canada. It is an important junction for the transportation of agricultural goods and energy supplies through highways, railways, and pipelines in Canada and to the United States of America. Part of the existing infrastructure and future expansion around the town has to be constructed in the badland areas. Material erosion causes serious damage to these vital facilities in both the vertical and horizontal direction. The former causes such problems as potholes in roadways, subsidence in railway tracks and sagging in pipelines between the supporting posts while partial washout around bridge abutments and retaining walls and channelling on embankment shoulders leads to lateral instability. These problems are multiplied when the supporting or the supported soils are periodically and/or differentially wetted and dried.

Given the rapid development of civil infrastructure in the Canadian Prairies, there is a growing need to determine the suitability of marginal lands for construction. The main objective of this paper was to characterize badlands with respect to precipitation. First, a literature survey was conducted to understand the effect of precipitation on the geological evolution of badlands. Second, an extensive field observation program was carried out at Avonlea, to develop a clear understanding of the selected site. Third, representative soil samples were collected from three distinct surfaces, namely: an upper slope made up of cemented sandstone, a mid-slope on weathered mudrock and a relatively flat basal pediment. Fourth, index properties were determined to classify the various in situ soils and evaluate their engineering behavior.

Geology and climate

Table 1 gives a summary of the various arid and semi arid areas with the reported occurrence of badland sediments (Thomas 1998). The mean annual precipitation on badlands in such climatic regions ranges between 170 and 500 mm. This three-fold variation in rainfall indicates that precipitation is not the only factor, but its interplay with geology is responsible for the evolution of badland profiles. Geological materials associated with the formation of badlands are

fine-grained argillaceous sediments under the generic term 'shale'. Depending on the degree of lamination, undulation, bedding and clay content, shale can be referred to as bedded silt, siltstone, mud-shale, clay-stone or mudstone (Potter et al. 1984). Cementing agents, such as iron oxide, calcite and clay minerals, significantly influence the behaviour of such materials when exposed to alternate wetting and drying cycles and the resulting mechanical erosion (Cerdà 2002).

With a harsh climate, the Canadian Prairies provide a natural environment for badland development in favourable geological settings. Deposition of most of the sediments in the region began in the Late Cretaceous (around 70×10^6 years B.P.) when a shallow sea covered the area (Christiansen 1979). During that time, the interior part of the Prairies, which lies close to the former shoreline, was an environment of wet deltas with thriving swamps. The rocks outcropping along the Red Deer River valley evidence fluctuating sea levels and regular shifts in the shoreline. The major rock layers in the interior region of the Prairies are divided into the following (Trimble 1980):

1. Oldman Formation: the oldest, up to 100 m thick, consisting of yellow sandstone, siltstone and shale, developed during the Cretaceous.
2. Dinosaur park Formation: 80 m thick, comprising red sandstone, siltstone, shale and thin coal layers, deposited by meandering rivers.
3. Bearpaw Formation: the youngest, about 350 m thick, consisting of dark brown and black marine sediments, laid down as a glacial deposit.

The development of badlands in southern Saskatchewan began around 15,000 years B.P. when the overlying glaciers started to melt. The preceding scouring action of the advancing glaciers rendered the surface rocks easily erodible. The melt water cut the exposed materials, creating steep-sided channels and deeply incised rills. The fluvial activity intensified as the runoff increased to form floods, such that huge volumes of less resistant Cretaceous rocks were washed away and deposited on the plains. In general, the weathered materials were transported at a rate faster than soil formation or plant growth. Presently, large seasonal climatic variations lead to similar erosion patterns in the region.

The Avonlea badlands fall into a semi arid climate zone. The average annual temperature in the area is 3.2°C with minimum and maximum values of -15°C in January and 19.6°C in July, respectively. Likewise, the average annual precipitation measures 365.6 mm with a minimum value of 10.1 mm in February and a maximum value of 64.4 mm in June. Such extensive contrasts in temperature and precipitation result in interesting phenomena at the soil surface. During winter, precipitation is in the form of snow and is therefore dumped on the ground, which remains frozen from

Table 1 Summary of badlands in arid and semi-arid environments

Annual rainfall (mm)	Location	Age and materials
500	Central Huanghe (Yellow river) valley, China	Pleistocene loess mainly comprising of silts and clays (smectite, illite and kaolinite)
450	Agri-basin, Basilicata, Italy	Pleistocene marine clays (smectite) and silts with interbedded sand, soft shale and mudstone
450	Little Missouri Badlands, North Dakota, USA	Palaeocene clays (smectite, chlorite and kaolinite) and mica rich materials
450	Kraft Badlands, Wyoming, USA	Tertiary sandstone
450	Badlands National Monument, South Dakota, USA	Oligocene poorly consolidated clays (smectite and illite) and silts with channel sandstone
450	Western Colorado, USA	Cretaceous marine shale with thin coal/sandstone lenses rich in smectite, illite, chlorite, and mica
355	Cheyenne river basin, Nebraska, USA	Oligocene clay (smectite), sandstone interbedded with mudstone, siltstone and shale
350	Kasserine area, Central Tunisia	Cretaceous marls illite, kaolinite and smectite with overlying clay loam and sandy soils
350	Red Deer valley, Alberta, Canada	Upper Cretaceous highly smectitic shale interbedded with clay-ironstone and sandstone
350	Almeria–Alicante region, Spain	Cenozoic and Triassic marls, silt, shale and sandstone
300	Rif mountains, Morocco	Pliocene marine sediments of alluvial and colluvial deposits clay mainly illite and kaolinite
220	Chaco river basin, New Mexico, USA	Cretaceous friable sandstone thin coal beds and thick mudstone of Kirtland and Fruitland Formations
135	Borrego Springs, California, USA	Pleistocene poorly consolidated gravelly sand and intercalated lacustrine clay and silt
100	Clement Markham Inlet, Ellesmere Island, Canada	Quaternary glacio-marine sand, silt and clay
90	Northern Negev, Israel	Palaeocene marls and soft clay

October to March. The large accumulations of winter snow are melted during April, thereby leading to severe erosion of the surface soils. During the summer months, both temperature and precipitation are high and result in alternating dry conditions between successive rainfall events. These periodic saturation and de-saturation phenomena contribute to mechanical disintegration of the exposed strata. Further, short-term freeze–thaw cycles due to daily temperature changes in spring (March and April) and fall (October and November) also add to soil erosion in the top 1–2 m layer of the sediments. Overall, soil erosion at the investigated site is governed by freeze–thaw and wet-dry cycles. Azam et al. (2007) identified several interrelated physical processes (abrasion, particle crushing, growth of mineral and ice crystals and slaking due to volume changes in clay minerals) which occur under such climatic conditions.

Field investigations

The field investigations covered an area of approximately 10 km². Detailed observations were made in different

climatic conditions and differentiated distinct badland surfaces, slope angles, material types and erosion patterns.

Figure 1 shows the general layout of the Avonlea badlands and the variable erosion patterns in the different materials. Three distinct surface soils were found: greyish brown cemented sandstone (CS), a mid-slope formed in olive grey weathered mudrock (WM) and a relatively flat, light grey basal pediment (BP). The 6–12 m high cemented sandstone had the steepest slopes that generally ranged between 60° and 80° but in some places were up to 85°. Gentle slopes (2–5°) characterized the 0.1–0.3 m high weathered mudrock which overlaid the 2–4 m high steep-sided (45–60°) unweathered material. The 0.3–1 m deep basal pediment consisted of alluvial sediments, usually occurring at the lowest elevation and with slopes of <2°. The cemented sandstone exhibits slope instability in the central mound (angle of repose slopes c. 40°) and rills and gullies in the peripheral slopes. It was found to be connected directly with the basal pediment (background slopes) or through an intervening mudrock layer (foreground).

Figure 2 shows the in situ materials in dry and wet states. An ironstone layer bisected the cemented sandstone,

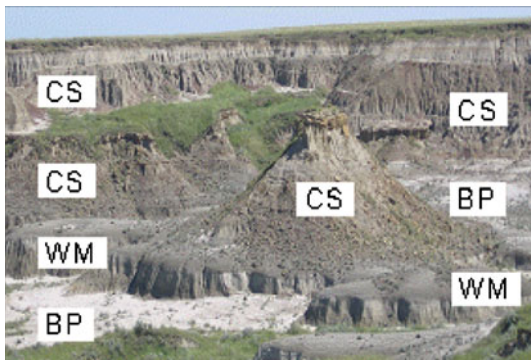


Fig. 1 General layout of Avonlea badlands

allowing the lower part to desiccate more quickly in comparison with the upper part (Fig. 2a). The intricately connected rill network in the lower part was composed of approximately equidistant 350–400 mm thick tubular rills. Together with the steep slope angles, these rills facilitate runoff, which occurs almost instantaneously even under light rainfall (Imeson and Verstraten 1988). In the upper part of the profile, the surface was rain pitted and contained a pipe outlet. Figure 2b shows the impact of free falling raindrops which resulted in particle detachment from the soil surface. Overall, the surface material generally acts as a 1–2 mm thick “rind” that restricts water penetration to about 5 mm depth below the surface (Faulkner et al. 2003).

As seen in Fig. 2c, the weathered mudrock exhibited a distinct structure comprising of unconnected “popcorns” formed by desiccation-induced shrinkage cracking when the surface materials were exposed to periods of no rainfall and high temperature. Subsequent precipitation obliterated the aggregates due to water adsorption and the associated swelling of the clays (Fig. 2d). Surface runoff in the weathered mudrock is seen only after a lag time, which varies with the amount of expansive clays, the slope angle and the depth of the weathered zone (Kasanin-Grubin and Bryan 2007). Precipitation initially results in infiltration within the larger voids and adsorption by the clay aggregates. The “popcorn” growth eventually ceases when the soil attains saturation and the surface is completely sealed. The high water adsorbing and retention capacity of the material ensures negligible surface erosion.

The basal pediment was found to disintegrate easily, suggesting the absence of active clay minerals and the associated cohesion. As a consequence, this material is easily transported by surface water and deposited in flat areas. Figure 2e shows a thin (10 mm) layer of dry sedimented material over an antecedent rain pitted surface. The preservation of raindrops and material build-up shows the high erosion capability of the basal pediment. This deposit acts as a cover for the underlying layer that remains wet most of the time, irrespective of precipitation conditions at

the surface (Fig. 2f). The marginal cohesion of the basal pediment indicates that these materials are mainly derived from the easily erodible components of the cemented sandstone: negligible amounts of weathered mudrock are found in the basal pediment.

Laboratory characterization

The field samples were transported to the Geotechnical Testing Laboratory at the University of Regina where the index properties were determined. The specific gravity (G_s) was determined according to the ASTM D854-06e1. The grain size distribution analyses were conducted in three stages:

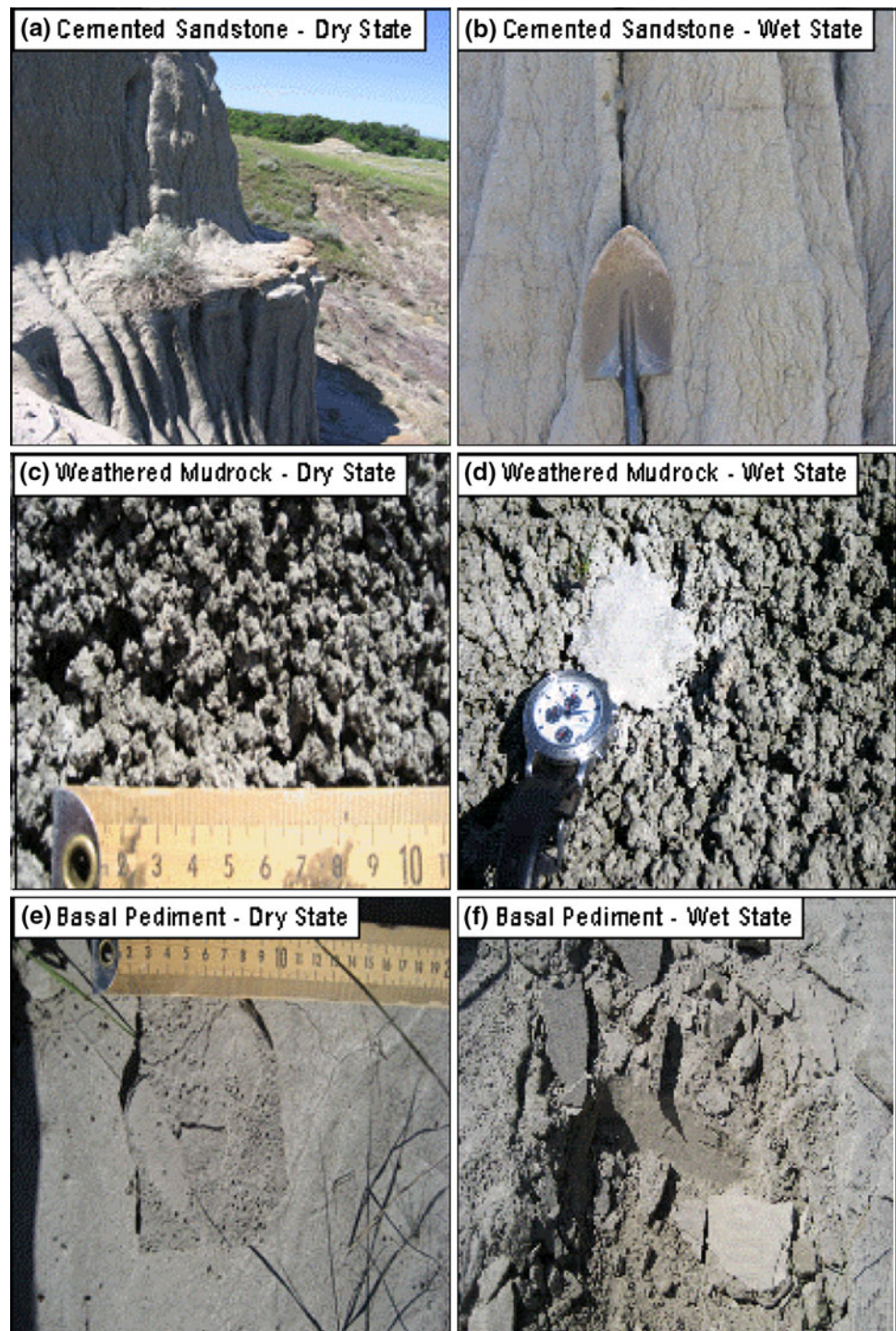
1. dry sieving according to ASTM D6913-04(2009)—although air-dried samples were used instead of oven dried samples to preserve the grain sizes found in the field;
2. wet sieving using distilled water to simulate the effect of precipitation on grain size distribution; and
3. hydrometer analyses on material finer than 0.075 mm in accordance with ASTM D422-63(2007), to determine the actual grain sizes of the fines. Material coarser than 0.075 mm was defined as sand and that <0.075 mm as fines, including both silts (0.075–0.002 mm) and clays (<0.002 mm).

The consistency limits were determined according to ASTM D4318-05 and the samples classified according to ASTM D2487-06e1 using the Unified Soil Classification System (USCS).

Table 2 gives a summary of the index properties of the investigated samples. The specific gravity of all of the samples was found to be higher than 2.75, indicating the presence of clays and/or metallic minerals. The liquid and plastic limits (w_l and w_p , respectively) explained the amount and electro-chemical activity of the clay minerals in the samples. The weathered mudrock exhibited the highest water intake followed by the cemented sandstone.

Figure 3 gives the grain size distribution of the samples. When dry, the amount of sand and fines in the cemented sandstone were found to be 92 and 8%, respectively (Fig. 3a). The sand size fraction was reduced to about 75% under wet conditions, which is related to particle breakage due to the presence of water and the dispersing agent [sodium hexametaphosphate (NaPO_3)₆]. These data indicate that precipitation can convert the cemented sandstone from a well-graded fine to coarse sand and silty sand (SW-SM) to primarily a silty sand (SM). Only 6% clay size material was enough to have relatively high consistency limits ($w_l = 40\%$ and $w_p = 31\%$) indicating a moderate water holding and water adsorbing capacity of the sample. This clayey material

Fig. 2 Wet and dry states of samples based on site observations



provides the necessary cementation to the soil and explains the presence of up to 12 m high steep slopes on site. Under unsaturated conditions, the soil derives friction from interlocking between the coarse grains as well as some suction. Both of these parameters contribute to shear strength and hence to the stability of the exposed slopes in the study area.

Figure 3b gives the grain size distribution of the weathered mudrock. On wetting, the grain size reduction

was quite pronounced (from 95 to 17% sand size). The high proportion of fines created a soil matrix with negligible erosion of the sand particles and transformed the well-graded fine to coarse sand (SW) to a silt of high plasticity (MH). Despite the 40% clay size fraction, the consistency limits ($w_l = 68\%$ and $w_p = 46\%$) of this sample indicate the presence of a small amount of active clay mineral. The high amount of fines in the weathered mudrock is

Table 2 Summary of geotechnical index properties

Parameter	Cemented sandstone		Weathered mudrock		Basal pediment	
	Dry	Wet	Dry	Wet	Dry	Wet
G_s	2.78	2.78	2.85	2.85	2.76	2.76
-0.075 mm (%)	8.0	24.8	5.0	83.4	25.6	58.6
-0.002 mm (%)	–	6.0	–	40.0	–	1.9
D_{10} (mm)	0.08	0.01	0.13	–	–	0.01
D_{30} (mm)	0.15	0.10	0.56	–	0.08	0.03
D_{60} (mm)	0.21	0.18	1.54	0.01	0.12	0.08
C_u^a	2.55	13.80	11.80	–	–	9.76
C_c^b	1.30	4.23	1.58	–	–	1.37
w_l	–	39.9	–	67.6	–	24.5
w_p	–	31.2	–	45.9	–	21.9
I_p	–	8.7	–	21.7	–	2.6
Classification ^c	SW-SM	SM	SW	MH	SM	ML

^a Coefficient of uniformity, $C_u = D_{60}/D_{10}$

^b Coefficient of curvature, $C_c = (D_{30})^2/(D_{10} \times D_{60})$

^c Unified soil classification system

associated with a high air entry value and a high water storage capacity. The sealing action of the high plasticity silt is responsible for the marginal erosion susceptibility of such materials in the field.

Figure 3c gives the grain size distribution of the basal pediment, which again showed a decrease in the sand size material on wetting (from 75 to 40%). Comparison of the wet and dry grain size distributions in Fig. 3a and c indicates that fine materials are washed from the cemented sandstone, transported over the weathered mudstone and deposited as basal pediment (Fig. 3c). The higher silt and fine sand content of the basal pediment is due to the fact that silt and fine sand is preferentially transported and deposited by water. The pediment surface is the least resistant sediment especially when wet. The low consistency limits ($w_l = 25\%$ and $w_p = 22\%$) in combination with a high amount of fines (59%) and little clay size materials (2%) indicate that this sediment is very unstable when saturated and vulnerable to fluvial erosion.

Construction implications

The above findings have important implications for the development and maintenance of civil infrastructure in the Avonlea badlands. New construction should be based on thorough site exploration and laboratory testing of the surface soils. Field investigations must identify critical locations most susceptible to erosion by including the following observations in the program:

1. Comprehensive topographic mapping to determine the spatial variability and mutual interaction of surface sediments
2. Orientation of hills and troughs to understand the moisture flux boundary conditions along the exposed strata

3. Soil profiles over a depth of 10–20 m to determine material heterogeneity and potential weak zones for pipe flow.

Likewise, geotechnical testing must focus on the determination of the collapsibility and compressibility properties of the basal pediment and the cemented sandstone as well as the swell-shrink-consolidation behavior of the weathered mudrock. From the perspective of erosion alone, linear engineering facilities such as highways, railways and pipelines should be routed away from the basal pediment and possibly away from the cemented sandstone. If that is not possible due to economic or strategic reasons, compaction of the marginal materials could be carried out with or without chemical (lime, cement) and mechanical (sand, gravel) admixtures. Maintenance of existing facilities depends on the nature and extent of deterioration. Based on experience with other prairie badlands (such as those in Drumheller, Alberta and Big Muddy, Saskatchewan), the two main repair strategies recommended for the Avonlea badlands include surface grouting for erosion control and deep anchoring for slope stability.

Summary and conclusions

The interaction of precipitation with geological materials is responsible for the development of badlands in arid and semi arid regions; the engineering evaluation of such marginal lands is pivotal for economic growth in southern Saskatchewan. The main conclusions of this study of the erosion susceptibility of Avonlea badlands are summarized as follows:

1. The Avonlea badland has three distinct surface sediments: an upper slope of cemented sandstone, a mid-slope on weathered mudrock and a relatively flat basal pediment.

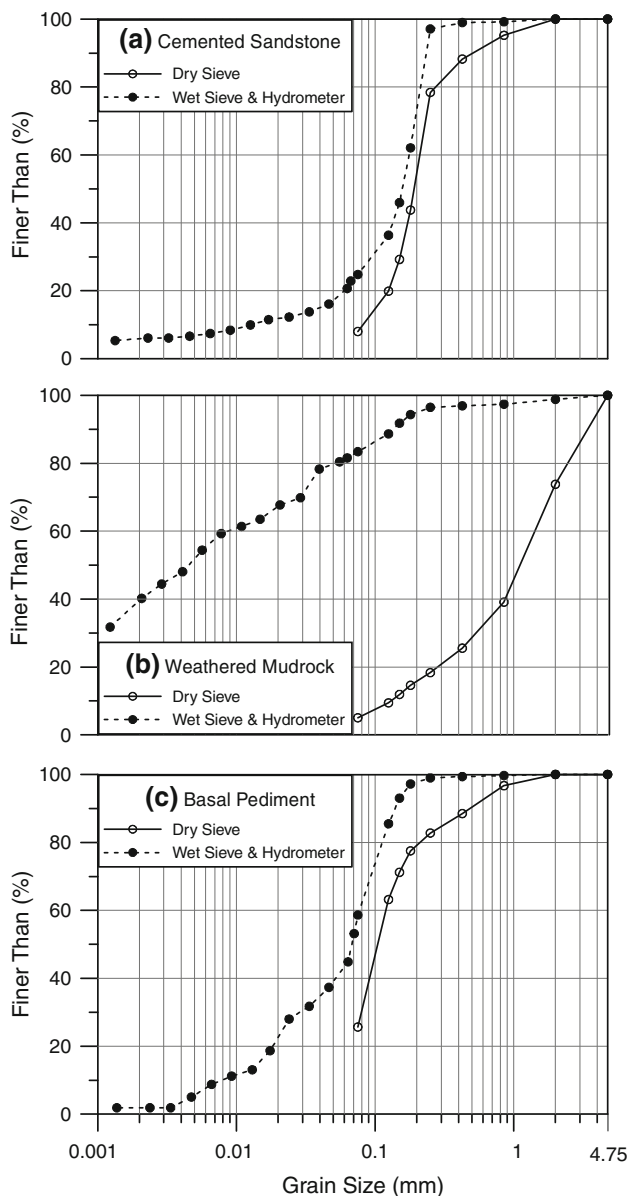


Fig. 3 Grain size distribution

2. Each of the surface soils is affected differently by the same rainfall event. Field investigations revealed the presence of rills and gullies in the steep cemented sandstone slopes, sealing of desiccation cracks and “popcorn” structures in the weathered mudrock and an alluvial deposition on the basal pediment surface.
3. Precipitation results in a reduction in grain size that, together with consistency limits, explains the water retention capabilities of soils. Erosion susceptibility is

highest in the basal pediment which has only 2% clays, followed by the cemented sandstone (cementation by 6% active clays) and then by weathered mudrock (cohesion due to 40% clay).

4. With wetting, the fines increased by 16% in the cemented sandstone, 78% in the weathered mudrock and 33% in the basal pediment. Consistency limits indicated moderate water adsorption for cemented sandstone, high water adsorption for the weathered mudrock and low water adsorption for the basal pediment.

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