ENGINEERING GEOLOGICAL CONSIDERATIONS FOR DAMS CONSTRUCTED ON THE PASKAPOO-PORCUPINE HILLS FORMATIONS IN WESTERN ALBERTA

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ABSTRACT
The Paskapoo Formation and its southern equivalent, the Porcupine Hills Formation are a regionally significant lithostratigraphic unit that underlay the western portion of the South Saskatchewan River Basin, within which numerous dams and reservoirs have been constructed since the early 20th century. The PSF has undergone renewed studies since 2013 as two proposed flood mitigations projects for Calgary are located on the PSF: the Springbank Offstream Reservoir, which is currently under construction, will divert flows from the Elbow River during a 1:200 flood event; and a proposed dam site along the Bow River at the Glenbow Ranch, is currently under consideration by the Government of Alberta. The paper provides an up-to-date synopsis on the engineering geological considerations when designing, constructing and operating dams, spillways and reservoirs that are constructed on the Paskapoo and Porcupine Hills Formation. This paper will focus on aspects such as geological heterogeneity, design parameters, uncertainty and anisotropy, rock mass characteristics, geohazards and hydrogeological considerations. Case studies from existing and proposed dam sites in Alberta are presented.

RÉSUMÉ
La Formation de Paskapoo et son équivalent sud, la Formation de Porcupine Hills, sont une unité lithostratigraphique d'importance régionale qui sous-tend la partie ouest du bassin de la rivière Saskatchewan Sud (SSRB), dans laquelle de nombreux barrages et réservoirs ont été construits depuis le début du 20e siècle. La PSF a fait l'objet d'études renouvelées depuis 2013, car deux projets d'atténuation des inondations proposés pour Calgary sont situés sur la PSF : le réservoir Springbank Offstream, qui est actuellement en construction, détournera les débits de la rivière Elbow lors d'une inondation de 1:200 ; et un site de barrage proposé le long de la rivière Bow au Glenbow Ranch, est actuellement à l'étude par le gouvernement de l'Alberta. Le document fournit un résumé à jour des considérations géologiques d'ingénierie lors de la conception, de la construction et de l'exploitation des barrages, des déversoirs et des réservoirs qui sont construits sur la formation Paskapoo et Porcupine Hills. Cet article se concentrera sur des aspects tels que l'hétérogénéité géologique, les paramètres de conception, l'incertitude et l'anisotropie, les caractéristiques de la masse rocheuse, les géorisques et les considérations hydrogéologiques. Des études de cas de sites de barrages existants et proposés en Alberta sont présentées.

1 INTRODUCTION

The Paskapoo Formation (PSF) and its southern equivalent, the Porcupine Hills Formation (PHF) are a regionally significant lithostratigraphic unit that underlay the western portion of the South Saskatchewan River Basin (SSRB), within which numerous dams and reservoirs have been constructed since the early 20th century. Notable dams constructed on PSF and PHF foundations include the Dickson and Oldman River Dams, which are owned and operated by Alberta Environment and Parks (AEP); the Bearspaw Dam, which is owned and operated by TransAlta, and the Glenmore Dam, which was constructed by the City of Calgary. These existing dams are used primarily for hydroelectric power generation, water storage, irrigation, water quality improvement, flood attenuation, recreation, apportionment commitments, and ice jam flood reduction.

The PSF has been subjected to renewed studies since 2013 as two planned dam projects are sited on PSF foundations: the Springbank Offstream Reservoir, which is currently under construction and will divert flows from the Elbow River during a 1:200 flood event; and the Glenbow Ranch Dam Site, which is one three options along the Bow River currently under consideration by the Government of Alberta.

The PSF and PHF typically comprise non-marine, olive-brown mudstone interbedded with fine- to coarse-grained, brownish-grey, cross-stratified sandstone and siltstone (Alberta Geology Survey (AGS), 2013), with subordinate limestone, coal, pebble conglomerate and bentonite layers. It represents a sequence of high-energy fluvial floodplain sedimentation associated with the Laramide Orogeny (Hamblin, 2004; Mei, 2019) and was final phase of the foreland evolution in the Western Canada Sedimentary Basin (WCSB).

The presence of marine and non-marine clay shales within the WCSB, together with glaciotectonic deformation, and valley rebound are a significant factor in the design, construction and safe performance of dams in the Prairie-region (Morgenstern, 1977, 1979, 1989; Rivard, 2014; Stead, 2015) and have been extensively studied. However, outside of the Oldman River Dam, previous studies have tended to focus more on the performance of dams constructed on marine clay-shales such as the Bearspaw Formation (Jaspar and Peters, 1979), Lea Park Formation, and Clearwater Formation (Morgenstern, 1988; Nicol, 2004; Martens and Charron, 2007; Cameron, 2013; Bayliss et al, 2014).

The PSF and PHF have been extensively investigated for buildings (Lo et al, 2009; Lo, 2011; Qu et al, 2010; Janes and Lardner, 2017; Osborn et al, 1998; Oswell et al, 1998), slope stability problems (Hardy et al, 1998; Stepanek and Rodier, 1980), light railways, water infrastructure and tunnels (Heinz et al, 2010) in Calgary; and for groundwater extraction. However, there is minimal up-to-date literature related to dams and reservoirs constructed on the PSP and PHF with the recent most studies dating back to the early 1990's with construction of the Oldman River Dam in Southern Alberta (Divachi et al, 1989; Sinclair et al, 1989; and Washuta et al, 1989).

This paper provides an up-to-date synopsis on the geotechnical and engineering geological considerations when designing, constructing and operating dams, spillways and reservoirs on PSF and PHF foundations. This paper will focus on aspects such as geological heterogeneity, design parameters, uncertainty and anisotropy, rock mass characteristics, geohazards and hydrogeological considerations. Case studies from existing and proposed dam sites in Alberta are presented.

2 GEOLOGICAL CHARACTERISTICS

2.1 Stratigraphic Framework

The PSF and the PHF are the youngest formations within the WCSB encountered in the and Foothills, Southern Plains and West Central Plains. It is underlain locally by the Coalspur, Willow Creek and Scollard Formations (AGS, 2019) . The regional extents are approximately of 66,000 km^2. It comprises an arcuate, eastward-thinning clastic wedge associated with the Alberta Syncline and ranges from 90 m thick in the Eastern Alberta to 3 km in southwest Alberta (Hamblin, 2004).

Demchuk and Hill (1991) divided the PSF and PHF into three members. The oldest and lowermost Haynes Member is dominated by massive, coarse-grained channel sandstones that form a regionally extensive and apparently continuous unit up to 100 m thick. The middle Lacombe Member is the dominant component and is characterized by interbedded overbank siltstone, mudstone, shale, and coal with minor fine- to medium-grained channel and splay sandstones. The youngest and uppermost Dalehurst Member consists of interbedded sandstone, siltstone, mudstone, and shale.

2.2 Depositional Setting

The pronounced heterogeneity, scale-effects and anisotropic geotechnical properties of the PSF and PHF are controlled by its depositional setting.

The PSF and PHF were deposited in a foreland depositional basin associated with uplift of the Rocky Mountains between 66 and 56 MA. Depositional settings comprised proximal, arid uplands and conglomeratic alluvial fans related to thrust activity on the western margins, medial fluvial coastal plain channel sandstones and overbank fines, and distal plain lacustrine and coal swaps (Dawson et al, 2004; Hamblin, 2004; Jerzykiewicz, 1997). Ongoing sedimentation would have resulted in burial and lithification; however, further regional tectonic uplift and isostatic rebound resulted in the erosion and fluvial downcutting of post-Paleocene sediments from the WCSB between 56 and 2 MA. It was estimated that up to 3000 m bedrock was removed through erosion in Southwestern Alberta by Burns et al (2010).

2.3 Characteristics

2.3.1 Fluvial Sandstones

The fluvial sandstones are characterized as light grey, yellow to cream, fine to coarse grained quartzose and chert-rich sandstone units. They are channelized, laterally extensive to lenticular, vertically-stacked and incised into surrounding overbank mudstones units with a sharp, basal erosional contact. The bedding thickness can range between 0.5 and 15 m and the beds can extend laterally for 150 m (Hamblin, 2004). The thinner beds, typically less than 1 m thick have lateral extents up to 50 m (Grasby et al, 2008). Sedimentary structures comprise crossbedding, bedding planes, laminations, ripple marks and variations in grain size (Crocq, 2010).

The unconfined compressive strength (UCS) of the fluvial sandstones are significantly higher than the adjacent mudstones and can range between 40 and 100 MPa.

2.3.2 Non-marine Mudstones

The fluvial sandstones are interbedded within grey to olive-brown, calcareous, sandy siltstones and mudstones. The thickness ranges between 1 and <50 m but outcrops are often poorly exposed due to weathering and slaking. The clay mineralogy is predominantly illite (40-45 %) and smectite (25 – 45 %) with subordinate chlorinate (5-15 %). Montimorillite (up to 15%) can be encountered locally. Dark grey, carbonaceous mudstones (often referred to as clayshales) and bentonitic-rich may be present within the non-marine mudstones. These can be slickensided and brecciated.

The UCS strength of non-marine mudstones is significantly lower than the adjacent sandstones and can be encountered as overconsolidated stiff clays or very weak rocks. The UCS can range between <1 and 36 MPa depending on the weathering, degree of lithification, fabric, and chemical composition. They are often heavily weathered and fissured when exposed in outcrops.

2.3.3 Geographical Facies Domains

Jerzykiewicz (1997) proposed five regional facies domains based on different paleoclimatic and depositional settings.

- Smoky River Domain: typically comprises lacustrine mudstones of alluvial plain and lacustrine origins, and coal swamp deposits, with minor sandstone beds.

- Athabasca Domain: typically comprises thick, alluvial fan clast supported conglomerates, sandstones, and the uppermost Obed Coal Zone
- North Saskatchewan River Domain: typically comprises thick lacustrine overbank mudstones with vertically-stacked, channel sandstones
- Bow River Domain typically comprises thick mudstones with thick, meandering, channel sandstones
- Porcupine Hills Domain: typically comprises thick mudstones with paleosols, and laterally confined, anatomizing channel and stacked, braided channel sandstones.

2.3.4 Hydrogeological-focused 3D Models

Recent studies for aquifer characterization have provided further insight into the regional 3D distribution of sandstone and mudstone lithologies in the PSF and PHF using groundwater and oil and gas well data (Chen et al, 2007; Grasby et al, 2008; Parks and Andriashek, 2009; and Lyster and Andriashek, 2012; Quartero et al, 2015).

The Alberta Energy Regulator (AER) and AGS recently expanded on the earlier studies to develop a regional-scale 3D property model of 'sandiness / shaliness' and porosity that can be used to conceptualize highly porous sandstones and regional permeability (Mei, 2019). The study concluded that the volume of the PSF and PHF is approx. 55 % shale and 45 % sandstone, and broadly correlates with the division proposed by Demchuk and Hills (1991). Modelling trends suggested that a < 50 m thick basal sandstone unit, correlating with the Haynes Member is regionally present and overlain by an approx. 300 m thick unit comprised predominantly of mudstones with subordinate sandstones that correlate with the Lacombe Member.

2.4 Structural Geology and Joint Patterns

The structural geology and joint patterns of sandstone units in the PSF and PHF are controlled by the orogenic processes that formed the Rocky Mountains (Faure et al, 2004; Hardebol et al, 2007). There is an abrupt transition between the Front Ranges and the Foothills, which comprises a 40 km wide zone of closely spaced, low displacement thrust faults (Osborn et al, 2006) called the Cordillerian Deformation Zone (CDZ), within which the western portion of the PSF and PHF are present.

The PSF and PHF typically exhibit a pattern of regional stress-induced fracture with negligible displacements closer to the Rocky Mountains (Burns et al, 2010). The open sets of vertical fractures trend SW–NE, which is orthogonal to the Rocky Mountains and is considered to coincide with postulated mean fluvial direction (Bell and Bachu 2003; Grasby et al. 2008) and the with dominant stress directions associated with formation of the Rockies and basin evolution. Deviations from the SW–NE fracture pattern are thought to be from conjugate fracture patterns and / or lithological controlled differential stress release (Sinclair et al, 1989).

Jointing is best developed in the sandstones, silty sandstones and cemented siltstones, whereas mudstones did not typically exhibit developed joints. The jointing is typically controlled by the bed thickness, although persistent joints can extended across several units.

The bedding of the PSF and PHF is typically sub-horizontal with a dip between 0.5 and 2° to the west, although, local variations can be encountered. The presence of the Alberta Syncline and other regional-scale folds can locally influence the dip and strike.

3 ENGINEERING GEOLOGICAL AND GEOTECHNICAL CONSIDERATIONS FOR DAMS AND RESERVOIRS

3.1 Presence of Weak, Slickensided, Clayshales Beds

Similar to the marine formations within the WCSB, the non-marine PSF and PHF also contains thin beds of weak, slickensided, high-plasticity, clay-shale, and/or bentonite layers. These are formed by post-depostional tectonic processes, valley rebound and glaciotectonic deformation (Morgenstern, 1988).

These have been encountered in the PSF and PHF during construction of the at the Oldman River Dam (Divachi et al, 1989; Divachi et al, 1991; Sinclair et al, 1989; Hendry et al, 2019), Dickson Dam and the Springbank Offstream Reservoir, which are discussed further in Section 4 of this paper.

The presence of these weak layers can have a significant impact on the design, construction and safe operation of dams. It is common practice in Alberta and Saskatchewan to assume that only the residual effective strength can be mobilized for the stability of an earthfill dam unless geotechnical investigation proves otherwise (Morgenstern, 1988; Rivard, 2014).

3.2 Swelling from Unloading and Wetting

The excavation of spillways and deep core trenches in the PSF and PHF can often result in swelling within the mudstone units. During excavation for a spillway, the mudstones may undergo rapid excavation / unloading, consolidation from the subsequent construction of concrete structures and time-dependent strength loss (referred to as softening). Fissured, overconsolidated clays and intact clayshales can exhibit a brittle-type stress-strain curve and dilatancy at low to medium stress levels in triaxial compression tests and direct shear tests. The behaviour changes from brittle to ductile as the confining pressure increases with a non-linear failure envelope at low stress levels (Yoshida et al, 1990). The state of stress around the excavation spillway would change and swelling in the clay / mudstone can occur, allowing localized opening of fissures. Suction is generated by the unloading. These fissures will remain open at depth due to the strength of the clay.

When rainfall or water from reservoir filling infiltrates the openings, the moisture content increases and the clay along the fissures swell further. This can result in increasing voids ratio, the development of hard clay 'cores' surrounded by softer clays and a weaker interlocking condition in the clay / mudstone mass. Cohesive strength loss and a reduction in dilatancy occurs and more fissures open. This is characterized by the lowering of the envelope and a decrease in the non-linearity at low stress levels to a fully-softened condition, which is equivalent to a normally consolidated clay. This mechanism can lead to long-term slope failures in clays and mudstones (Martin and Read, 2018; Yoshida et al, 1991; Chandler, 1984; Morgenstern, 1989; 1977; Skempton, 1970; Terzaghi, 1936).

3.3 Geological Heterogeneity and Lithological Correlation

It is apparent from the earlier sections of this paper and the case studies provided in Section 4 that the correlation of lithological units within the PSF and PHF for engineering purposes is difficult due to the depositional setting, scale-effects and practical limits / costs of geotechnical investigations. Correlation of individual units is difficult due to inter-fingering, persistence and lenticular nature of the beds, lateral facies changes, transient distributary channels, and the lack of diagnostic lithological characteristics.

Site characterization of the dam foundations in the WCSB requires reasonably conservative assumptions to account for this uncertainty. Typical practice is to assume that the dam foundations comprises a laterally extensive, mudstone unit for slope stability analysis unless the exhaustive geotechnical investigations can prove otherwise and prove that laterally extensive sandstones units are present with a high degree of confidence. Conversely the presence of laterally extensive sandstone must be considered for the characterization of seepage and pore-pressure responses beneath the dam foundation and when analyzing reservoir leakage.

The mudstone units exhibit a prominent anisotropic fabric due to the sedimentary bedding in comparison to the sandstone units, which typically exhibit orthogonal systems of sub-vertical joints. This typically accommodated in the design of embankment dams by apply anisotropic strength functions in stability analysis that account for lower friction angles between 0 and ±5° to the horizontal that represent the residual strength and a cross-bedding strength, that is typically higher and represents the peak strength.

3.4 Hydrogeological Characteristics and Seepage Control Requirements

The PSF and PHF are considered regionally important aquifers and have been extensively extracted by groundwater wells. Hydrogeological characterization is complex and not associated with identifiable stratigraphic zones but is controlled by paleo-depositional lenticular sandstone bodies embedded in low permeability mudstones, shale and siltstones with highest water production occurring in the fluvial sandstones or fracture zones (Grasby et al, 2008; Burns et al, 2010).

The in-situ hydraulic conductivity of this unit can vary considerably. At the Springbank Offstream Reservoir, it ranged between 6.5 x 10-5 and 6.1 x 10-8 m/s.

Grout curtains have been used at dam sites in the PHF. The Oldman Dam and spillway is underlain by a 1.3 km long grout curtain that extends from the right abutment of the spillway to the valve chamber in the Diversion Tunnels. The purpose of the grout curtain was to reduce seepage passing beneath the dam (and spillway) and the uplift pressures associated with the seepage; and prevent piping of erodible materials in the bedrock joints in the foundation under the effects of hydraulic gradients (Hartaier et al, 2002).

At the Bearspaw Dam, a grout curtain was installed beneath the concrete structures to fill lens shaped cavities 300 mm thick and up to 10 m diameter that were discovered during drain hole drilling during rehabilitation works in the 1980’s (Nunn et al, 1987).

4 EXAMPLES OF DAMS CONSTRUCTED ON THE PASKAPOO AND PORCUPINE FORMATIONS

4.1 Bearspaw Dam

The Bearspaw Dam is an extreme consequence, low-head, run-of-the-river, 17 MW hydroelectric development located on the Bow River, upstream of Calgary. It is owned and operated by TransAlta. The dam was constructed between 1953 and 1954 with subsequent dam safety upgrades implemented between 1985 and 1987.

The dam is a maximum 20 m high and 275 m long zoned embankment dam. It contains a central impervious core with shells of sand and gravel, with a core trench excavated to bedrock. The concrete spillway comprises an ogee crest and the three 15.2 m wide by 9.6 m high gates supported by piers with a maximum width of 4.6 m. The powerhouse comprises an intake structure formed from a series of slabs which form the water passage and span between mass concrete piers projecting from the mass concrete of the powerhouse sub-structure. A side-channel overflow spillway is present on the northern abutment.

Boreholes records from 1983 to 1935 indicate that the foundation comprises thin to thick, sandstones, mudstones and siltstones encountered at different elevations. During construction, the alluvium beneath the core was excavated and the core was founded directly on sandstone at the excavation surface, but mudstones are present beneath this unit. Direct shear testing undertaken on mudstone samples resulted in an average peak $\Phi'p = 32^{o}$, lower bound $\Phi'p$ peak = 23^{o} and a residual $\Phi'r = 12^{o}$ (Nunn et al, 1987).

The author understands that there has been no foundation displacement in the PSF since slope inclinometers were installed. Given the lack of a grout curtain beneath the dam, piezometers typically respond cyclically to the reservoir fluctuations.

4.2 Dickson Dam

The Dickson Dam is an extreme consequence dam, impounding the Glennifer Reservoir, located on the Red Deer River in central Alberta. It is owned and operated by AEP. The dam regulates water supply to the downstream users in the Red Deer River basin, flood attenuation, improved water quality, recreation, hydropower production and apportionment. The dam system incorporates a 15 MW capacity hydropower station, which is currently operated by Algonquin Power & Utilities Corp (Simpson and Sengupta, 1981).

The dam system comprises a 40 m high and 650 m long, zoned earthfill dam across the Red Deer River and several kilometres of saddle-dykes (north, east, and south dykes). The impounded Glennifer Reservoir is 11 km long, 2 km wide and has a storage capacity of approximately 203,000 dam3 at FSL. Water management is provided by a five-bay concrete service spillway and two power tunnels (formerly diversion tunnels) for hydroelectric generation, and an auxiliary and emergency fuse plug spillway

At the dam site, the Red Deer River Valley is a steep-sided channel formed by erosion of the river through the glaciogenic units into the PSF. Prior to dam construction, the valley was approx. 500 m wide with 30 m high valley walls. The river channel was 75 m wide and 4 m deep along the thalweg.

Geotechnical investigations indicated that the dam foundation comprised interbedded sandstones, siltstones, and mudstones with minor beds of limestone and lignite.

The sandstones and siltstones were fine to medium-grained, greenish-grey and well cemented. The thickness typically ranged between 0.1 and 7 m. The UCS ranged between 30 to 70 MPa. The location of the diversion tunnel portals and spillway headblocks were dictated by the competent sandstone and siltstone layers. The distribution of sandstone and siltstone units were lower in the left bank compared to the right bank.

The mudstones were stiff, medium-plastic, silty clays grading to medium soft, mudstones. The majority of the mudstones were friable and easily broken. X-ray diffraction indicated that the clay-sized fraction comprised 80 % of kaolinite and illite, with subordinate chlorite and Montmollonite. The Montmollonite content ranged between 9 and 21 %.

The mudstones units contained occasional 20 to 150 mm thick, slickensided, brecciated or mylonitic layers of medium to high-plasticity clay. The correlation of these units was difficult, although there was a slight increase towards the valley walls, suggesting a valley rebound mechanisms. The residual strength ranged between 14.7 and 29°. This resulted in the adoption of a residual $\Phi'r$ = 15º for design purposes.

4.3 Glenbow East Dam Site Option

The GoA is currently exploring options to build additional flood and drought storage capacity on the Bow River. Three reservoir options were identified in 2017 as part of the Phase 1: Concept Study, of which a new reservoir was located on the PSF between Cochrane and the Bearspaw Dam at the western edge of Calgary. The site is currently being studied as part of the Phase 2: Feasibility Stage (AEP, 2022).

The Phase 1 study was primarily desk-study with supplemental geological reconnaissance and unmanned aerial vehicle flights used to geological map outcrops along the Bow River. No project specific-geotechnical intrusive investigation had been completed for Phase 1.

Existing water well data was used to develop a concept-level site geology model, which indicated that the PSF comprised horizontal to sub horizontal, interbedded mudstones, siltstones and sandstones (Wood, 2020), and was significantly eroded across the broad river valley due to glacial advances and postglacial fluvial events.

4.4 Glenmore Dam

The Glenmore Dam is an extreme-consequence dam located on the Elbow River within Calgary. It is owned and operated by the City of Calgary for water supply. The dam was constructed between 1930 and 1932 with upgrades in the 1980’s to handle the PMF and again, in 2022 to provide additional flood storage.

The dam system is unique compared to the other dams discussed in this paper as it comprises a 30 m and 320 m long high concrete gravity dam founded on the PSF. It comprises 16 gravity monoliths, an ogee overflow spillway, non-overflow section, the screenhouse and pumphouse, a stilling basin, and a bridge deck.

The dam was constructed in a narrow valley postglacial valley which was formed by the downward erosion of the Elbow River through glacigenic deposits into the PSF. The PSF observed in the slopes of the river valley comprise interbedded, thin units of sandstone, mudstone, and siltstones. Massive channel mudstones can be frequently observed downstream of the dam itself (KCB, 2015).

4.5 Oldman River Dam

The Oldman River Dam is an extreme-consequence dam located on the Oldman River in southwest Alberta. It is owned and operated by AEP and is used primarily for the management of irrigation water supply under the Prairie Provinces Water Board Master Agreement on Apportionment. The dam system incorporates a 32 MW hydroelectric generation plant, which is jointly owned by ATCO and the Piikani Nation

The earthfill dam is a 76 m high and 700 m long, zoned earthfill and rockfill dam that was constructed across the Oldman River. The impounded Oldman Reservoir has a full supply level (FSL) of El. 1118.6 m and a maximum reservoir level of El. 1124.5 m. It provides 490,000 dam3 of live storage over its operating range. The spillway comprises a 145 m wide headworks structure with seven vertical lift roller gate, 336 m long chute spillway and flip bucket.

Geotechnical investigations identified 22 weak continuous bedding planes (design seams) within the PHF. 11 continuous bedding planes shears were identified in the abutment and 11 were identified in the valley base. The low shear strength available along these bedding plane shears controlled the design and layout of the dam system. Based on a detailed investigation conducted by the designers, 14 of the 22 weak seams were determined to govern the design of the dam and spillway. The weak seams were found to comprise laterally extensive, continuous shear planes, groups of closely spaced sub-parallel shear-planes or as brecciated zones with anticipated ‘field’ residual shear strengths between 11.5° and 17°.

Divachi et al (1989; 1991) described the following characteristics of the weak seams in the PHF at the Oldman River Dam site:

- Occur along contacts between relatively strong and weak units, such as sandstones.

- Exhibit parallel bedding.
- Occur as single shear plans, groups of closely spaced sub-parallel shear-planes or as brecciated zones.
- Single shear planes are usually less than 2 mm thick and occasionally up to 10 mm thick. Groups can be up to 75 mm thick.
- Thin shear plans often contain fillings of silt and clay gouge.
- Commonly associated with thin, dark, carbonaceous claystone marker beds.
- Continuous for distances of 100’s m, sometimes up to 1km.
- Curved shear plans or splays can occasionally develop off the main bedding plane shear. These splayed planes can form a braided network of shears within a claystone bed.
- Frequency is greatest in the upper 10 to 15 m of bedrock, possibly attributed to weathering.

The author understands that there has been no foundation displacement in the PHF beneath the dam since construction.

The spillway excavation has undergone displacement upon a previously identified weak seam known as R1. The average rate of movement was up to 1.04 mm/month during construction. Displacement continued along the R1 seam at a lower rate after the reservoir filled in 1991, when it cycled between 0.37 and 0.87 mm/month between March 1991 and November 1994. The deformation was caused by a combination of stress relief / rebound in the rock due to the excavation; changes in the rock stress regime caused by reservoir filling; and swelling of claystone due to saturation. Whilst the deformation has slowed considerably since 1994, it is still ongoing as of 2020 (Hendry et al, 2019).

4.6 Springbank Offstream Reservoir

This project is a flood diversion and storage system currently construction by the GoA to divert and temporarily store flood waters from the Elbow River Basin. It comprises a comprises a diversion structure, a diversion channel, earthfill dam and storage reservoir
with no permanent pool. SR1 is designed to operate alongside the Glenmore Dam in Calgary to limit flood flows within the Elbow River downstream of the Glenmore Dam to less than 160 m3/s during design flood events.

The PPF subcrops beneath the east dam abutment, the eastern portion of the dam footprint between approximate Station 21+400 and 24+000 m, the Low-level outlet and the reservoir. Rotary drilling and geological mapping was undertaken to determine the presence of weak mudstone layers within the PPF. The following observations were made as part of this geotechnical assessment:

- Visual descriptions of recovered rock cores indicated that there is extensive weak, mudstone/claystone lithological unit beneath the dam footprint, particularly in the eastern portion
- Slickensides were occasionally encountered in the mudstone units
- UCS tests indicated that the mudstone / claystone units had a compressive strength between 0.7 and 2 MPa
- Index testing on selected clay/mudstone layers indicated that the Liquid Limit (LL) typically ranged between 35 and 44 %. However, a LL of 79 % was encountered locally.
- Direct shear testing resulted in considerable scatter. A lower-bound $\Phi'r = 12°$ for the zone of weak mudstone in the eastern portion of the dam.

5 CLOSING REMARKS

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6 REFERENCES

Bayliss, A.I, Philip, L, Masterson, K, Wong, R, Rahman, M, Hepp, D, Clarke, M, Martens, S. & Elbanna, M. 2014. The Geological Influences of Glacially Rafted Clearwater Formation on the Design and Operation of an External Tailings Facility. Proceedings-GeoRegina 2014. Canadian Geotechnical Society Annual Conference. Regina. Saskatchewan. Sept 29–Oct 1, 2014.

Bell, J.S., and Bachu, S. 2003. In situ stress magnitude and orientation estimates for Cretaceous coal-bearing strata beneath the plains area of central and southern Alberta. Bull Can Petrol Geol. Vol 51 (1)

Burns, E.R., Bentley, L.R., Hayashi, M., Grasby, S.E., Hamblin, A.P., Smith, D.G. and Wozniak, P.R.J. 2010: Hydrogeological implications of paleo-fluvial architecture for the Paskapoo Formation, SW Alberta, Canada: a stochastic analysis; Hydrogeology Journal, 18(6): p. 1375–1390.

Cameron, R. 2013. Case Studies in Soil Parameter Selections for Clay Foundations. Canadian Geotechnical Society Cross-Canada Presentation Spring Lecture Tour 2013.

Chandler, R.J. 1984. Recent European experience of landslides in overconsolidated clays and soft rocks.’’ Proc., 4th Int. Symposium on Landslides, Toronto, 1, 61–81

Chen, Z., Grasby, S.E. and Wozniak, P.R.J. 2007. Paskapoo groundwater study part VI: Aquifer transmissivity estimation and a preliminary data analysis of the Paskapoo Formation, Alberta; Geological Survey of Canada

Dawson, F.M., C.G. Evans, R. Marsh, and R. Richardson. 1994. “Chapter 24 – Uppermost Cretaceous and Tertiary Strata of the West Canada Sedimentary Basin.” Geological Atlas of the Western Canada Sedimentary Basin. Calgary.

Demchuk, T.D. and Hills, L.V. 1991. A re-examination of the Paskapoo Formation in the central Alberta Plains: the designation of three new members; Bulletin of Canadian Petroleum Geology, 39(3): p. 270–282.

Divachi, M.M. Sinclair, B.J., Hartmaier, M.M., Baggot, B.L., and Peters, J.E. 1989. Shear strength of the Oldman River Dam Foundation. Presented at 30th General

Meeting of Canadian National Committee, ICOLD; and 42nd Canadian Geotechnical Conference

Grasby, S.E., Chen, Z., Hamblin, A.P., Wozniak, P.R.J. and Sweet, A.R. 2008. Regional characterization of the Paskapoo bedrock aquifer system, southern Alberta; Canadian Journal of Earth Sciences, 45(12): p. 1501–1516.

Hamblin, A.P. 2004. Paskapoo-Porcupine Hills formations in western Alberta: synthesis of regional geology and resource potential; Geological Survey of Canada, Open File 4679, 30 p.

Hartmaier, H., Divachi, M., Dharmawardene, W., and Sinclair, B. 2002. Design, Construction and Performance of the Oldman River Dam Grout Curtain. 55th Canadian Geotechnical Conference and 3rd Joint IAH-CNC/CGS Conference, Niagara Falls, Ontario

Janes, M., and Lardner, T. 2017. The Bow, EnCana: Design, Monitoring, and Results of a Deep Excavation in Downtown Calgary. Journal of the Deep Foundations Institute Vol 4(1)

Jaspar, J.L. and Peters, N., 1979. “Foundation performance of Gardiner Dam” Canadian Geotechnical Journal, Vol. 16: pp 758 – 788

Jerzykiewicz, T. 1997. Stratigraphic framework of the uppermost Cretaceous to Paleocene strata of the Alberta Basin; Geological Survey of Canada, Bulletin 510, 121 p

Lo, K.Y., Micic, S., Lardner, T., and James, M. 2009. Geotechnical properties of a weak mudstone in downtown Calgary. GeoHalifax ’09, 62nd Canadian Geotechnical Conference. Halifax, Nova Scotia

Lo, K.Y. 2011. The Effects of Deep Excavations in Soils and Rock on Adjacent Structures (The R M Hardy Address). 2011 Pan-Am CGS Geotechnical Conference

Lyster, S. and Andriashek, L.D. 2012. Geostatistical rendering of the architecture of hydrostratigraphic units within the Paskapoo Formation, central Alberta; Energy Resources Conservation Board, ERCB/ AGS Bulletin 66, 103 p

Martens, S. N. and Charron, R, 2007. “Detailed Geotechnical Investigation of the Clearwater Clay Shale” 60th Canadian Geotechnical Conference, Ottawa: pp 1709-1716

Mei, S. 2019. Three-dimensional property modelling of the Scollard, Paskapoo and Porcupine Hills formations in southwest Alberta; Alberta Energy Regulator / Alberta Geological Survey,

Morgenstern, N.R. 1989. Recent experience with dam foundations on clay-shale in western Canada. Special Lecture, Proc., 12th Int. Conf. on Soil Mechanics and Foundation Engineering, 4

Morgenstern, N.R. 1979. Geotechnical behaviour of clay shales - An overview. Int Symp Soil Mech

Morgenstern, N. R. 1977. Slopes and excavations, State of the Art Report, Proc., 9th Int. Conf. on Soil Mechanics and Foundation Engineering

Nicol, D. 1994. The Syncrude Mildred lake Tailings Dyke Redesign, Transactions of the 18th International Congress on Large Dams, Durban, South Africa, 7-11 November, ICOLD

Parks, K. and Andriashek, L. 2009. Preliminary investigation of potential, natural hydraulic pathways between the Scollard and Paskapoo formations in Alberta: implications for coalbed methane production;

Prior, G.J., Hathway, B., Glombick, P.M., Pana, D.I., Banks, C.J., Hay, D.C., Schneider, C.L., Grobe, M., Elgr, R. and Weiss, J.A. 2013. Bedrock geology of Alberta, AER/AGS Map 600.

Osborn, G., Stockmal, G., and Haspel, R. 2006. Emergence of the Canadian Rockies and adjacent plains: A comparison of physiography between end-of-Laramide time and the present day. Geomorphology. Vol 75 (3)

Quartero, E.M., Leier, A.L., Bentley, L.R. and Glombick, P. 2015. Basin-scale stratigraphic architecture and potential Paleocene distributive fluvial systems of the Cordilleran Foreland Basin, Alberta, Canada; Sedimentary Geology, 316: p. 26–38.

Rivard, P.J. 2014. Case Histories of Embankment Dams on the Prairies.

Sinclair, B.J., Hartmaier, H.H., Davachi, M.M. and Peters, J.E. 1989. Geology of the Oldman River Dam Site. Presented at 30th General Meeting of Canadian National Committee, ICOLD; and 42nd Canadian Geotechnical Conference

Skempton, A.W. 1970. First-Time Slides in Over-Consolidated Clays. Geotechnique. Vol 20(3)

Stead, D. 2015. The Influence of Shales on Slope Instability. Rock Mechanics and Rock Engineering. Vol 49

Tavenas, F. and Leroueil, S. 1981. Creep and failure of slopes in clays. Can. Geotech. J., Vol 18 (1)

Terzaghi, K. 1936. Stability of slopes of natural clay.’’ Proc., 1st Int. Conf. on Soil Mechanics and Foundation Engineering

Washuta, A.S., Simonsen, C.P.S, and Davachi, M.M. 1989. Design of the Oldman Dam Spillway. Presented at 30th General Meeting of Canadian National Committee, ICOLD; and 42nd Canadian Geotechnical Conference

Wood. 2020. Bow River Reservoir Options Phase 1: Concept Assessment

Yoshida, N., Morgenstern, N.R. and Chan, D.H. 1991. Analysis of Softening Effects in Mudstone and Over-Consolidated Clays. Soils and Foundations. Vol. 31(1)