

Chapter 3

Chemistry: An Essential Key to Understanding High-Sensitivity and Quick Clays and to Addressing Landslide Risk

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Abstract The property of silty-clay to clayey-silt quick clays, whereby apparently solid soil transforms to the liquid state when subjected to sufficient stress, derives from chemical factors: mineralogy (low activity); depositional environment (marine-to-brackish conditions causing flocculation and high water content); and post-depositional chemical changes (development of cementation and displacement of marine-to-brackish water by infiltrating rainwater). The stability of slopes developed by river incision is affected (negatively) by physical factors (drainage and fluctuating water tables) and chemical weathering reactions that have led to weak, fissured, blocky, nodular structures. Immediate causes of quick clay landslides are commonly the physical factors of: river erosion; high water contents in the fissured slopes; and human actions. Regardless, the characteristics of the resulting landslides are primarily determined by the chemical factors.

3.1 Introduction

Chemical influences on physical factors dominate the development of quick clays. Knowledge of these influences is essential to understanding and managing the challenges that the physical properties of quick clays present. Indeed, chemistry's dominating role in quick clay development (Fig. 3.1) and behavior provides the starting point for developing approaches to ameliorate the quick-clay landslide problem and other challenges presented by these unusual natural materials.

'Quick clay', used alone, refers to the undisturbed material, *in situ*, and to samples that retain their microstructure. After structural breakdown, by any means, it has been transformed to 'disturbed', 'remolded' or 'post-failure' quick clay.

The vast majority of quick clays accumulated in marine to brackish water during the late stages of the last continental glaciations. Their main mineral components are

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Factors producing high undisturbed strength	
Depositional	Post-depositional
Flocculation ^{1,2} <ul style="list-style-type: none"> • Salinity¹ • Polyvalent cations dominate² • High suspension concentration 	Cementation <ul style="list-style-type: none"> • Rapidly developed • Slowly developed Slow load increase Time-dependent diagenetic changes
Factors producing low remolded strength	
Material properties <ul style="list-style-type: none"> • Domination by low activity minerals^{1,2} 	Decrease in liquid limit > decrease in water content <ul style="list-style-type: none"> • Leaching of salt¹ • Dispersants² Reducing Conditions Inhibition of high-swelling smectite formation Minimal consolidation

1 Essential in marine clays 2 Essential in fresh water clays (Modified from Torrance 1983, 2012)

Fig. 3.1 The general model for quick clay development

glacially ground silt- and clay-sized particles of common rock-forming minerals – mostly quartz, feldspars, amphiboles, micas and chlorites. They also contain iron oxide nanoparticles, produced by grinding. The marine sediments in Scandinavia, Canada (east of Hudson Bay) and immediately adjacent states of the USA, and in coastal British – are similar, but not identical in terms of their mineralogy and development. Sensitive marine sediments in Ariake Bay, Japan, represent a major variation (Torrance and Ohtsubo 1995). They are ‘post-glacial’, having accumulated during the sea-level-rise period that accompanied glacial melting. They differ in being dominated by high-iron, low-swelling, smectitic clay minerals and volcanic ash. They have similar high sensitivities and bearing capacity problems and their sensitivity development has followed the same basic rules as the Scandinavian and North American sediments.

3.2 Development of High Sensitivity

Salinity-induced flocculation gives the sediment strength, and its open structure holds a high water content. High sensitivity develops when fresh water entering the sediment displaces the salt water. Salinity reduction to <2 g/l creates a situation

where, if the flocculated structure breaks down, the soil behaves as a liquid; quick clay has been produced. In Eastern Quebec and Labrador, cementation by iron oxides greatly increases the undisturbed soil strength and increases the sensitivity and has implications for the post-failure strength as well.

3.3 Cementation in Eastern Canadian, Sensitive Clays

Cementation, which increases undisturbed strength, is important for sensitivity in parts of Quebec and Labrador. The Scandinavian, Japanese, British Columbian and Ottawa Valley sensitive clays are considered ‘soft’ – meaning ‘not cemented’.

It is not unusual to find the occasional small carbonate-cemented concretion at landslide sites. At Green Creek Valley in Ottawa, many concretions weighing 100 gm to several kilograms have been exposed by river erosion. The carbonate has locally impregnated the pore space. Their presence shows that, in water-saturated conditions, the carbonates, when in small amounts, prefer to congregate to form concretions, rather than to act as a widely dispersed cementing agent.

Within the St. Lawrence River Basin, the only compounds of sufficient abundance and low solubility to act as cementing agents are hematite and magnetite. Magnetite is more effective, probably because it has the highest stability toward weathering of the iron oxides (Murad 1988) and it is magnetic. From west to east in Quebec, the dominant iron oxide changes from: hematite (~1% by wt) in the Ottawa Valley (Torrance and Percival 2003); to magnetite at St. Leon le Grande, near Trois Rivières (Torrance et al. 1986). The magnetite almost certainly originated by grinding (to nanometer sizes) of magnetite-rich, iron ore (from western Labrador) during glacial transport outward and southward to where it ultimately co-sedimented with the other glacially ground minerals, in the Champlain, Laflamme and Goldthwaite Seas. The location and abruptness of the transition to magnetite dominance are undetermined; based on ice-flow patterns and terrain features, it probably occurs over a short distance near Joliette, about 60 km SSW of Trois Rivières. The degree of cementation trends higher towards the eastern portions of the marine sediment accumulation areas of Quebec and Labrador.

Studies on the effect of EDTA, as an extractant for iron oxides, have been conducted on clays from Outardes, Québec, in the Goldthwaite Sea (Loiselle et al. 1971) and from Labrador (Kenney et al. 1967); both locations lie ‘down-ice-flow’ from the Québec/Labrador magnetite deposits. In both cases, EDTA was percolated through undisturbed samples of cemented marine clay and the percolate was collected. The most Fe^{+3} that Loiselle et al. extracted was 0.94% of the soil dry weight. The most Fe^{+3} that Kenney et al. extracted was 0.37% of the soil dry weight. Bulk extraction by EDTA at the end of the latter experiment revealed that the percolation experiment, which extracted about 20% of the magnetite originally present, led to substantial decrease in the ‘*apparent*’ preconsolidation’ pressures. Another overall conclusions, from Mössbauer spectroscopy and the extraction

experiments, are that nano-crystalline magnetite co-sedimented with the other glacially ground minerals, and that it is a remarkable cementing agent.

In 'Landslides in Sensitive Clays' (L'Heureux et al. 2014), clays with cementation were commonly referred to as being 'over-consolidated'. This is misleading. It is preferable to think of them as exhibiting '*apparent preconsolidation pressures*' (Kenney et al. 1967), because their high resistance to consolidation arose from cementation, not by volume decrease from prior greater loading. In the consolidation context, they are, in a way, 'under-consolidated' in that relatively little post-depositional consolidation occurred, when compared to the non-cemented Champlain Sea sediments. This reconceptualization may be of little consequence if one is only concerned with bearing capacity; but arguably, it is very important in the context of sensitive-clay landslides. These '*apparently preconsolidated*' sediments have somewhat greater water contents than do non-cemented sediments bearing the same load. Consequently, their greater cementation and lesser consolidation results in greater hydraulic conductivities, which facilitates more rapid leaching of salt from the sediment, and to a lower post-failure strength. Where valleys are: deeply incised into sediments with cementation; the riverbanks high and steep; and the weathered, surface zone thin compared to the depth of quick clay that underlies it, the size and severity of landslides would be enhanced. The presence of cementation by magnetite at St. Jean Vianney, and the 'under consolidation' that resulted, were factors in the high fluidity of the quick clay debris. This affected both the on-site and the downstream impact of the landslide. This consequence of cementation is important in the landslide amelioration context.

3.4 Geomorphic Influences on Landslide Types

The sensitive marine clay landscapes of Eastern Canada and those of Norway and Sweden differ greatly. The Champlain Sea sediments accumulated as broad, level expanses into which rivers incised their valleys; hills are scarce in the Basin. In the Laflamme Sea Basin, level expanses are less extensive, although most marine sediment surfaces are remote from hills. In the Goldthwaite Sea Basin and through to Labrador much of the exposed marine sediment is within sight of rocky uplands. In Scandinavia, many of sensitive-marine-sediment areas abut rock uplands, particularly in coastal Norway. Even in muted topography north of Oslo, rock outcrops and glacial till knolls interrupt the marine sediment surface continuity. In Sweden, western coast marine sediments and those now inland along rivers are adjacent to rock uplands, as are the brackish-water, Baltic Sea sediments in the muted topography of eastern and southern Sweden. These different geomorphological settings influence salt leaching in important manners.

3.5 Leaching and Weathering Dynamics: Flat Expanses

On large flat areas, salt removal occurs by water infiltration through the soil surface. Near riverbanks, the flow path is short; further away, water follows longer and deeper paths through the sub-surface drainage system. Water infiltration is accompanied by the physical and chemical changes of soil profile development (soil scientist view) and weathering crust development (geotechnical engineer view). In addition wetting and drying, freezing and thawing, oxidative weathering and transport of soluble products develop a several meters thick weathered crust zone.

The near-surface processes change the originally massive structure of the surface zone and valley slopes. Roots and the soil fauna introduce organic matter into the soil to produce a few-centimeter-thick zone of friable aggregates, the A horizon, below which angular, blocky aggregates become increasingly large until a massive zone is reached. In eastern Canada, Eden and Mitchell (1970), described the upper angular, blocky zones as having a 'nodular' structure'. In these angular, blocky zones, the vertical surfaces of the aggregates, throughout their depth range, have 'cutans' (thin layers of clay, iron oxides and black organic material) on their surfaces. This presence of cutans indicates that the spaces between blocky units are open and occupied by air or water, depending on the hydrologic conditions. These open spaces in the weathering crust, particularly on slopes, are locations of weakness. Hence, the angular, blocky aggregation that dominate the river valley slopes, throughout the zone within which the water table fluctuates during floods and heavy rainfalls, contribute to slope instability; local riverbank failures commonly constitute the triggering events for sensitive clay landslides.

3.6 Leaching and Weathering Dynamics: Near Uplands

Adjacent to uplands, salt leaching proceeds differently. The marine sediment interfaces directly with areas where the water table is higher than the sediment surface. The resultant artesian pressures at the lateral and basal contacts cause flow of water through the marine sediment, displacing the salty pore water upward. The rain that falls on the surface penetrates only a short distance before it is deflected towards the drainage system. The weathered surface zone's interface with quick clay may be as shallow as one meter. Also, after salt water has been displaced to produce the leached quick clay, continuing upward flow of water may bring with it potassium and magnesium ions, weathered from potassium feldspars, illite, and chlorite) in an oxidizing environment, that will slowly decrease the sensitivity from the sediment base upward (Moum et al. 1971). Such situations are expected in Norway, Sweden (along the Gota River and elsewhere), and in Canada where nearby uplands create artesian pressures at the sediment base.

3.7 Landslide Types: Flows and Spreads

Quick clay landslides commence with a failure that involves mostly the fractured, nodular, weathered material of the riverbank. This failure is commonly triggered by the combination of erosion at the river bank base (which steepens the slope) and water saturation in the weathered zone (which decreases the frictional component of its strength). The landslide may be a ‘flow’ or a ‘spread’. A few slides exhibit elements of both types. Flows tend to occur in a step-wise fashion; whereas spreads tend to occur as a continuous, uninterrupted event. The different patterns arise from the transporting ability of the liquefied zone, which relates to the ratio of the thickness of the zone that liquefies relative to that of the low-sensitivity, weathered crust and any sensitive material above the failure zone that does not liquefy (Torrance 2012, 2014).

When related to the geomorphological influences, ‘flows’ tend to occur where salt leaching occurred from below (thin weathered crust), and ‘spreads’ where salt leaching was from above (thick weathered crusts). Hence, ‘flow’ slides should dominate in Scandinavia, while in eastern Canada, ‘flow’ slides are concentrated: (1) in the northern portions of the Champlain Sea Basin where the sediments are relatively shallow and adjacent to Canadian Shield uplands; (2) along river channels where the river is deeply incised and the liquefiable quick clay zone is very thick relative to the weathering crusts, as at St Jean Vianney in the Laflamme Basin (Tavenas et al. 1971), and the Rivière du Loup and Rivière Yamachiche basins west of Trois Rivières in the central Champlain Sea Basin (Karrow 1972); and 3) where sediments are in fjord-like settings such as the lower Rivière Gouffre valley near Baie St Paul in the Goldthwaite Sea Basin (Filion et al. 1991). In other situations, ‘spreads’ would be expected to be the norm. Demers et al. (2014) provide an inventory and some imagery of large landslides in Quebec. Some landslides exhibit elements of both flow- and spread-landslides.

3.8 Flow Slide Examples

In the 1951 ‘flow’ landslide at Ullensaker, Norway, the farm owner observed ‘fissures at the lower parts of the slope towards the brook’ (Bjerrum 1955). His awareness that the cracks could lead to a bank failure and subsequent landslide led him to evacuate his family to a neighbor’s farm. The slide occurred shortly after midnight, taking all the farm buildings and about 10 hectares of farmland. It left a ‘classic’ bottle-neck scar with a narrow opening to the creek valley.

On May 4, 1971, 31 people died in a disastrous flow slide at St. Jean Vianney, along the Petit Bras River, near Chicoutimi, Quebec (Tavenas et al. 1971). Ten days before, a 100 m long, river-bank failure extended 60 m into the steep and high river bank. It was discovered by the farm owner and photographed, but not

reported. On the evening of May 4, a St. Jean Vianney resident felt a slight “earth shaking” and could see Chicoutimi’s lights from her window (never before visible), phoned a neighbor to ask if she had felt anything. Neither interpreted these signs to indicate a landslide was under way. In contrast to the folk knowledge about quick-clay landslides in the Norwegian sensitive clays, local knowledge of quick clay landslides was almost non-existent in the Laflamme Basin. This is probably because few quick-clay landslides have occurred during historical times. The first scientific report on quick-clay landslides in the basin was published in 1968 (La Salle and Chagnon 1968), only 3 years before the landslide. The publicity that followed this landslide has narrowed the knowledge gap.

3.9 Spread Slide Example

For spread slides, the failure begins when a relatively thin, quasi-horizontal layer of quick clay near the riverbank slope, fails and liquefies, upon which, the riverbank soil commences its movement into the valley and the failure plane retrogressively advances into the landscape. Sequential breaking of the overburden into slightly-rotated slices and/or a horst and graben-like sequence of intact-triangular-ridges and debris-occupied-valleys follows. These features are pushed forward by an ongoing supply of new ridges and liquefied debris. The landslide ceases when the capacity of the valley or plain to accommodate more debris is exhausted. The stalled sequences of ridges and troughs, inside the scar and in the debris field beyond, leads these spreads to often be referred to as ‘ribbed’ landslides.

The 1989 landslide at St. Liguori, Quebec, which disrupted a golf course, was triggered by a night-time, riverbank failure that was followed, essentially instantaneously, by a rapidly-advancing retrogressive stage. The retrogression distance extended to include several hectares on which a single-storey house had been constructed. While the occupants were rudely awakened and their house was irreparably damaged, they ‘rode out the landslide’ without injury. Locat et al. (2014) discussed some of the apparent differences among spread-type landslides.

3.10 Chemical Amelioration of Sensitive Marine Clays

3.10.1 Salt Addition – NaCl

The first application of chemistry to a quick-clay landslide problem was in 1953 after a 100,000m³ spread at Bekkelaget destroyed 100 m of the highway connecting Oslo to the rest of Europe (Eide and Bjerrum 1955). The debris liquidity inhibited rebuilding of the highway. Professor Ivan Rosenqvist, University of Oslo,

demonstrated how mixing NaCl into the liquid debris would transform it into a plastic material of sufficient strength to allow reconstruction of the highway.

3.10.2 Lime Piles and Hydroxy-Aluminium Piles

Broms and Boman (1979) introduced 'lime piles' as a means of increasing the bearing capacity of sensitive clays. Unslaked lime is mixed into the sensitive soil, and pozzolanic (cementing) reactions of the calcium oxide with the aluminum-bearing minerals strengthen the soil. Lime piles have become a standard practice. Bryhn et al. (1983) investigated hydroxy-aluminium, $(\text{Al}(\text{OH})_{2.5}\text{Cl}_{0.5})$, as an additive to strengthen sensitive clays. It works if calcium carbonate is present, or if additives that generate the pozzolanic reactions are introduced. Over time, the strengthening effects of both methods extend into the untreated adjacent soil; the hydroxy-aluminium effects extend further and more rapidly. Neither method is readily adaptable to application over large areas, or great depths. Soil disturbance during mixing of additives into the clay, the number of piles required and the pile length limit the application of the pile methods to landslide amelioration.

3.11 KCl Introduction by Diffusion from Salt Wells

In the early 1970s, when a new highway intersection in Northeastern Oslo was designed, it was decided to use salt addition to increase the undisturbed strengths of the sensitive clay sediments. The salt would also reflocculate and strengthen high sensitivity sediments disturbed by construction activities. Moun et al. (1968) had demonstrated that K^+ diffused most quickly through samples of intact quick-clay, and was the most effective in increasing the undisturbed and remolded strengths. While Na^+ (0.99 Å) is smaller than K^+ (1.37 Å), hydrated Na^+ is larger than hydrated K^+ and its diffusion coefficient is only 2/3 that of K^+ . Also, hydrated K^+ has a greater affinity to cation exchange sites and a 50% greater effect on the soil behavior. 2629 salt wells of 15 cm diameter and 15–16 m depth, at a grid spacing of 1.5 m, were drilled over an area of 6000 m² and filled with solid KCl (Helle et al. 2017). Investigations a few years after installation showed remarkably improved geotechnical behavior, and the highway interchange was completed. Subsequently, 3 boreholes were investigated in 2002 and 2 more in 2013. The results are analyzed by Helle et al. (2016). Their assessment was that KCl salt wells are very promising. A long-term advantage of KCl is that, as leaching continues over centuries and the salt concentration gradually decreases, K^+ should remain as the dominant pore-water and exchangeable cation for centuries; consequently, the sediment's sensitivity will remain low. This approach is truly long term.

3.12 Chemical Amelioration of Landsliding in Sensitive Clays

The quick-clay landslide problem can be addressed by: 1) prevent the triggering landslide in the weathered riverbank; or 2) prevent the slide from advancing into the quick clay beyond the weathered zone. Strategy one requires: earthworks at the slope base and/or slope height and slope angle reductions. These actions have safety and soil disposal challenges that make them impractical for most sites. Strategy two can be addressed by chemical modification of the high-sensitivity clay adjacent to the weathering crust using salt wells; the design of the salt-well array would be site dependent.

KCl introduction by diffusion from salt wells is feasible: installation need not disturb the riverbank; the wells are of small diameter; and the hydraulic pressure remains hydrostatic. KCl diffusion progressively improves undisturbed and post-failure soil strengths (Helle et al. 2016, 2017); and is long term. KCl leaching should not pose a river water quality problem and the site can be avoided as a drinking water source. This approach should be very effective in Scandinavia, and in non- to lightly-cemented sediments in North America. It should also be beneficial in cemented, high-sensitivity sediments.

3.13 Concluding Remarks

The interactions of chemical factors – depositional environment, particle mineralogy, changes in pore-water chemistry, oxidizing or reducing conditions, cementation (or lack thereof) and more – in determining the physical properties of the post-glacial, sensitive, marine clays and in changing their behavior, pose a challenge to the geotechnical community. Limits to bearing capacity, susceptibility to disastrous landslides and the ease with which limits can be exceeded, demand that practitioners be familiar with their properties and how those properties can change, for better or worse, as a consequence of what seem to be innocuous actions. Chemistry played many roles in the development of the high sensitivity sediments; it shows great promise in providing solutions to problems, including for the most dramatic one of quick clay landslides.

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