

Is there a potassium-based solution to sensitive soil slipping within the Bay of Plenty?

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ABSTRACT

Landslides are common in sensitive, weathered pyroclastic soils in the Bay of Plenty (BOP). The clay mineralogy of these soils is dominated by halloysite, an inactive 1:1 clay mineral. Manipulation of cation content within the pore water of sensitive soils has been shown to improve *in situ* soil strength in illite-dominated soils in Norway. We present results of laboratory tests on the impact of altering cation status of a sensitive soil from the base of a large landslide at Omokoroa near Tauranga, BOP. Addition of KCl and KOH both reduced the liquid limit of the soil, a negative effect. In contrast, addition of K_2CO_3 caused an increase in the plasticity index of soil pastes. Soaking intact samples in K_2CO_3 for three weeks resulted in a considerable increase in peak stress in effective stress triaxial testing. These early results suggest that mitigation of sensitive soil landslides through increasing peak strength by addition of appropriate salts to the soil profile may be an option for mitigation of landslides in sensitive BOP soils.

1 INTRODUCTION

Sensitive soils are found across the globe, and have widely been identified as a significant contributor to slope instability. Most notably, sensitive soils can cause large, retrogressive landslides, resulting in serious hazards to infrastructure, the local environment, and human life (Quinn et al., 2011). Sensitivity is recognised as a considerable loss in strength on remoulding and is defined as the ratio of undisturbed to remoulded strength at the same moisture content. Young, clay-rich deposits from a variety of marine, lacustrine, and pyroclastic (tephra) environments have been reported as being sensitive (Rosenqvist, 1977; Torrance, 1983; Kluger et al., 2017). In New Zealand some of the most damaging sensitive soils are located within Bay of Plenty (BOP), eastern North Island. These soils are encompassed within altered Quaternary rhyolitic tephra deposits and reworked derivatives, and a key component is the presence in them of the clay mineral halloysite (Moon et al., 2015).

Recent reports from Norway indicate that a long-standing experiment has proven successful in the prevention of sliding within a sensitive soil landslide. Columns of potassium chloride installed in the glacially-derived sensitive soils (illite dominated) for a period of 30 years have produced improvements in peak undisturbed soil strength to the point that movement of the slide had been reduced to nil (Moum *et al.*, 1970; Torrance, 2014; Helle *et al.*, 2015). As a result, we postulate that the methodologies used by the researchers in Norway could be applied to the soils of BOP

with the ultimate goal of locally increasing peak shear strength in the soils. However, the clays differ in our tephra-derived soils from those of Norway (halloysite cf. illite), and the clay-cation interactions will be different. Hence, the aim of this paper is to investigate suitable salts that might be used to mitigate landsliding in the sensitive soils of BOP. We evaluate the most appropriate salt and the impacts its addition has on Atterberg limits and on peak strength under laboratory test conditions.

2 HALLOYSITE

Halloysite is a dioctahedral 1:1 clay mineral belonging to the kaolin sub-group (Joussein *et al.*, 2005; Churchman *et al.*, 2016). It is commonly formed in altered volcanic and tephra deposits, and within New Zealand these deposits are generally rhyolitic with the halloysite formed from rapid, low temperature alteration mainly of volcanic glass and also feldspar (Churchman and Lowe, 2012). Halloysite has a basal spacing of 7.2Å (dehydrated form) and 10.1Å (hydrated form), with the larger basal spacing deriving from the presence of interlayer H₂O ('water') between sets of octahedral (aluminol) and tetrahedral (silanol) sheets within the clay. The H₂O present within the clay is found in two forms: 'hole' water which solely interacts with the silanol sheet through forming hydrogen bonds with the oxygen of the silanol sheet; and 'associated' water which interacts with both the hole water and the hydroxyl groups on the aluminol sheet. This associated water acts as a bridge between the various sheets, and forms the intercalated water giving the increased basal spacing (Joussein *et al.*, 2005; Churchman *et al.*, 2016; Ferrante *et al.*, 2017).

Interactions between halloysite and various cations have been explored in the literature and indicate that surface interactions between halloysite and cations may be responsible for the bonding between clay minerals *in situ*. As a consequence, the manipulation of the cation content should produce results similar to those observed in Norway, though the cation and salt utilised may not be the same. Based on the literature, we suggest the ideal potential choices are narrowed to potassium salts: potassium chloride (KCl), potassium hydroxide (KOH), and potassium carbonate (K₂CO₃).

3 METHODS

Soils were sampled from a layer of sensitive soil within the Pahoia Tephra sequence at the base of the Bramley Drive landslide, Omokoroa. Kluger *et al.* (2017) describe details of the profile, sampling site, and sampling procedure. For our study, 12 sample pipes (50 mm inside diameter) were pushed into a prepared horizontal platform, dug out, and wrapped carefully to avoid moisture loss. Approximately 4 kg of bulk soil was additionally collected for Atterberg limit testing.

Atterberg limits were determined on soil pastes following standard methods (ISO/TS 17892-12:2004(E)) using a drop-cone penetrometer to determine liquid limit, and rolled threads for plastic limit. Initially soil from the site was re-moulded into a large homogenous paste with distilled water as the mixing medium. Atterberg limits were first tested on this baseline untreated paste. Next, equal-size portions of the homogenous paste were used in Atterberg limit testing, with the difference between these and the initial baseline being the use of a salt solution instead of distilled water to change the moisture contents of the sample. For each treatment, the pH of the soil mixture was measured by placing the probe directly into the mixed soil paste as outlined by Torrance (1999). Salts used for treatments were KCl, KOH, and K₂CO₃.

Treatment of soil cores prior to triaxial testing was achieved via submersion in a K₂CO₃ solution at 2 mol L⁻¹ strength and the initial electrical conductivity of the solution was measured before cores were placed in sealed plastic containers. Approximately 2.5 litres of solution were placed in each container, 4 soil cores were added to each, and the conductivity of the solution again

measured. The containers were sealed and placed in a dark room kept at a controlled temperature between 15 and 18 °C. The cores were treated for a period of 4 weeks.

Effective stress triaxial testing was undertaken following British Standard BS1377-8:1990. Samples were saturated to $B \geq 0.95$, then consolidated to effective confining stresses of 200, 280 and 355 kN m⁻² to reflect *in situ* stresses. Testing rates varied between 0.5 mm min⁻¹ to 0.524 mm min⁻¹ depending on consolidation characteristics. During testing, measurements were made every 30 seconds until 20% of axial strain was reached.

4 RESULTS

4.1 Atterberg limits

Atterberg limit results are presented in Table 1. Baseline results for liquid limit and plasticity index are in keeping with data for other halloysite-rich soils from New Zealand; the plastic limit determined here is higher than other determinations on New Zealand soils, but within the ranges described by Wesley (1973) for Indonesian soils rich in halloysite. As anticipated, the liquid and plastic limits are high, because of the interlayer H₂O within halloysite, but the plasticity index is moderate to low and the soil is thus not active.

Table 1. Atterberg limit test results. Published ranges of results for New Zealand halloysite-rich soils mixed with distilled water are from Moon (2016).

Treatment	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Activity	pH
Distilled water	92	78	14	1.1	4.8
KCl	79	74	5	0.3	4.4
KOH	83	72	11	0.7	8.7
K ₂ CO ₃	93	73	20	1.1	10.1
K ₂ CO ₃ (after 1 month)	92	72	20	1.1	10.1
Published ranges	42-99	29-67	10-46		

Surprisingly, KCl and KOH both reduced the liquid limit of the soil, whereas the plastic limit was reduced slightly for all treatments. As a result, the plasticity indexes of the soils treated with KCl and KOH are reduced markedly, the opposite of the desired effect, resulting in a reduced activity. In contrast, K₂CO₃ did not impact the liquid limit, but gave a reduction in plastic limit similar to that associated with the other treatments, resulting in a slightly increased plasticity index. Leaving the K₂CO₃ treated soil for a month and retesting showed no further change in Atterberg limits.

The pH measurements on the pastes made for Atterberg testing (Table 1) showed that the soil is characteristically acidic, with a pH of 4.8. Of all treatments only the K₂CO₃ raised the pH significantly enough to cause the soil to become basic (10.1), whereas KOH neutralised the soil (8.7) and KCl lowered the pH to 4.4.

4.2 Conductivity

The conductivity of the solute in which the soil cores were immersed was measured once a week following first immersion of the cores in the solutions. This was done to give an indication of the potential ion uptake by the soil. Over the first week there was a rapid uptake of ions from the solute to the soil for both sets of cores as overall conductivity dropped by approximately 50%; this rate of uptake continued over the second week of soaking (Figure 1). Little ion uptake appeared to be occurring after two weeks' immersion, as shown by the flattening out of the curves. Two curves appear as these plot the conductivities of two separate treatments that occurred simultaneously on the soil cores.

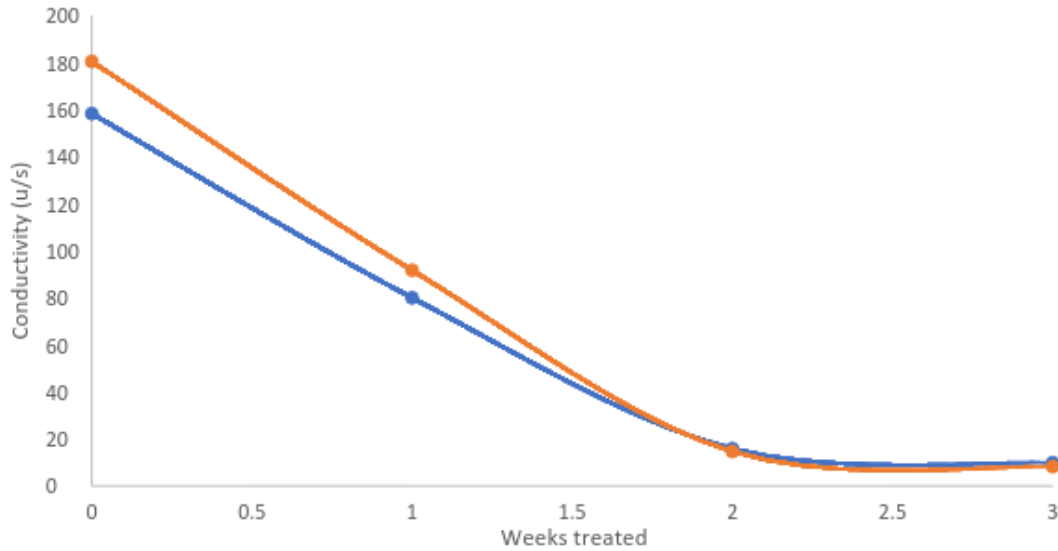


Figure 1: Graph displaying changing conductivity of solute during soil core treatment over time of treatment.

4.3 Triaxial testing

Table 2 details the key results from triaxial testing for both untreated (Un1-3) samples (saturated in distilled water), and treated (Tr1-3) samples which were immersed in K_2CO_3 solution for 3 weeks. Note that although samples were run to full extent of 20% of axial strain during testing, a malfunction with the data logger resulted in data being collected only for the first 10% of axial strain.

Table 2. Triaxial test conditions and results. ϵ = axial strain at point of failure, q = peak shear strength, and u = pore water pressure.

Sample	Confining Pressure (kPa)	ϵ failure (%)	q failure (kPa)	u failure (kPa)	Strain Softening (%)
Un1	205	6.48	151	50	12
Un2	280	1.53	227	174	35
Un3	355	1.09	313	195	41
Tr1	205	0.78	343	123	24
Tr2	280	0.9	424	153	32
Tr3	355	1.11	386	170	25

Figure 2 displays the deviator stress and pore water pressures measured during triaxial testing for both treated and untreated samples. It can be observed that for all confining pressures the peak shear strength of the treated samples is noticeably higher than that of the untreated samples. Indeed, even the lowest confining pressure of treated samples (Tr1, 205 kPa) exhibits a higher peak deviator stress than the untreated counterpart at highest confining pressure (Un3, 355 kPa). It is also worth noting the low variability of pore pressures, with the pore pressures of both 355 kN m⁻² samples displaying similar values of pore pressure as shear strain increased.

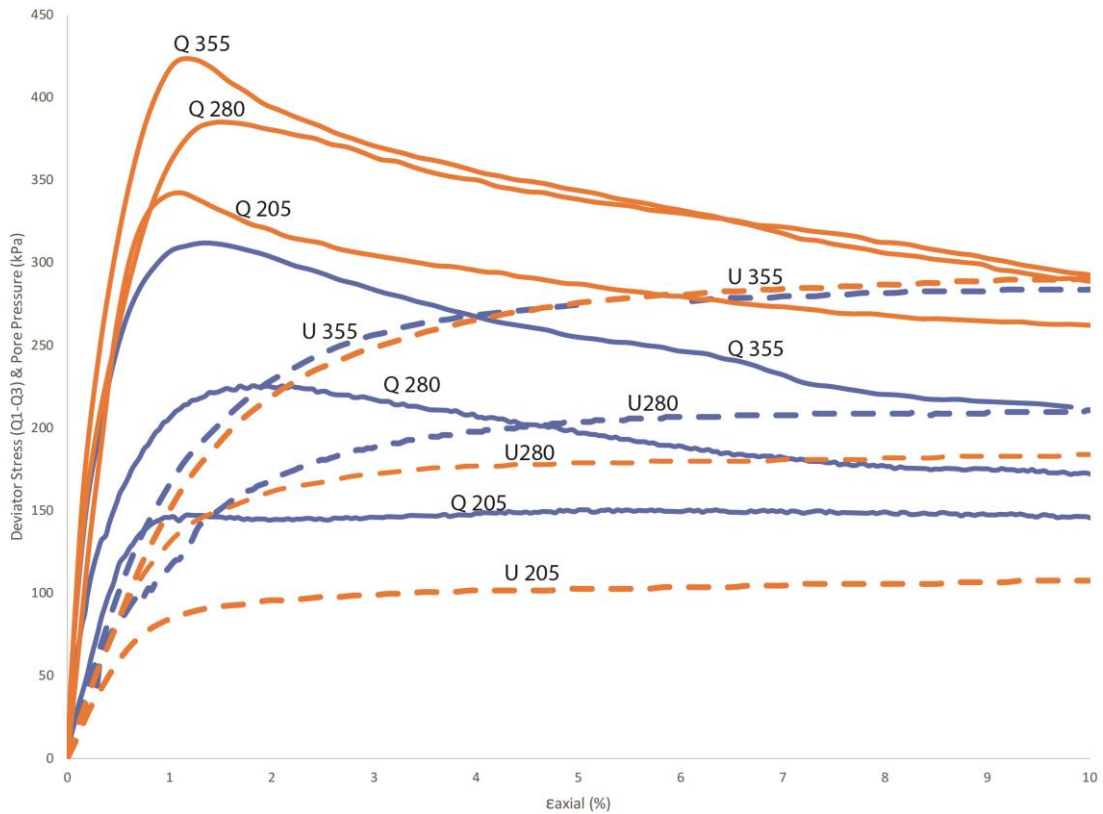


Figure 2. Graph displaying deviator stress (Q) and pore water pressure change (U) versus axial strain whether treated (orange) or untreated (blue)

Post-failure strain softening during testing is exhibited by all materials. Strain softening for untreated samples all showed an increase as confining pressure increased, whereas treated soil cores showed an inverse with a reduction in strain softening between the higher two confining pressures from 32% to 25%. Overall, strain softening tended to be less for the treated samples than for untreated samples (Table 2).

Stress path (p'/q') plots in the untreated soil cores showed a deviation to the left, indicating that slight contraction has occurred in the soil (Figure 3A). In contrast, for the treated soils, all curves deviate sharply to the left, thus indicating very clear contractive behaviour as the plots track down the critical state line.

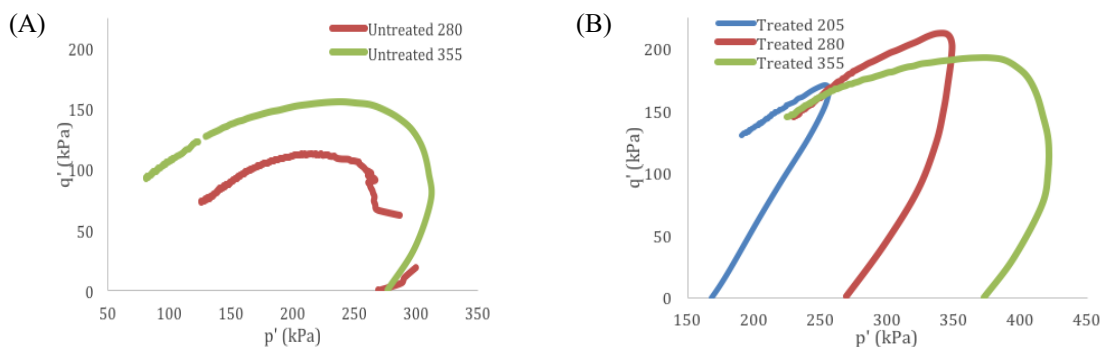


Figure 3. p' q' plots showing contraction of soil samples following failure at each confining pressure. (A) untreated samples, (B) treated samples.

5 DISCUSSION

Treatment with both KOH and KCl caused drops in the liquid limit, an unexpected result. Our hypothesis to explain this observation relates to the soil pH and the resulting reaction between the clay surface within the remoulded paste and the introduced salt solution. Theng & Wells (1995) undertook rheological tests on pastes of pure halloysite materials from various sites in New Zealand. They noted that for tubular and lath-type halloysite morphologies, the Bingham yield stress was strongly influenced by pH. They attributed this to charges on the crystal edges associated with protonation/deprotonation of exposed Al ions. At the point of zero charge (PZC) the edge surface is essentially uncharged; at pH values below the PZC the edges will be positively charged while at pH values above the PZC the edges will be negatively charged. For the samples evaluated by Theng & Wells (1995), the PZC occurred at a pH of approximately 6. The natural pH value for our soils (measured in distilled water) is acidic (pH 4.8). When KCl is introduced, dissociation of the salt means that the chloride ion forms a conjugate acid of hydrochloric acid (HCl), resulting in a lowered pH (4.4). While an overall positive edge charge might be expected to lead to enhanced interactions between edge surfaces and negatively-charged face surfaces of the halloysite minerals, in practice the interactions are mediated by cations within the pore fluid. We infer that due to the overall positive nature of the clay edges, the significant increase in K⁺ ions within the soil media results in a net dispersive effect within the soil, causing the observed drop in the liquid limit.

In contrast, treatment with K₂CO₃ resulted in a slight decrease in plastic limit, and an unchanged or slightly increased liquid limit (Table 1). Addition of K₂CO₃ caused a significant rise in pH (10.1), lifting the pH to well above the PZC identified by Theng & Wells (1995). Thus the edge charges on the clay minerals will be negative, and the abundant K⁺ ions are able to mediate a relatively strong attraction between negatively charged edge and face surfaces of the clay minerals. Unexpectedly, addition of KOH did not show the same impact, with liquid and plastic limits both depressed by this treatment, despite the pH rising above the likely PZC of the clay. We propose that this finding is due to the strongly amphoteric nature of the Al groups on the octahedral sheet edge resulting in bonding with the anionic OH⁻ groups as opposed to bonding with K⁺ ions, resulting in a loss of overall strength in the soil paste.

A possible reason why K₂CO₃ worked as opposed to the KOH could potentially lie within the likelihood of the salt to readily intercalate into the crystal lattice structure of the halloysite itself. As stated above, halloysite has two forms of bonded water within its structure: hole H₂O, and associated H₂O (Ferrante et al., 2017), with each H₂O layer influencing a different bonding characteristic of the clay. In case of the K₂CO₃ treatment, the salt may potentially have an influence on both the hole H₂O and associated H₂O within the clay. Previous studies examining the introduction of K₂CO₃ to clay pastes indicated that K₂CO₃ will readily intercalate into the halloysite structure, as indicated by an increase in basal spacing following treatment with K₂CO₃ (Garrett & Walker, 1959). Intercalating the K₂CO₃ into the structure increases the structural strength as the K⁺ ions actively form ionic bonds with the amphoteric aluminol groups on two separate octahedral clay sheets, with the potassium ion essentially forming an ionic bridge between the two sheets. This intercalation may contribute to the overall increase in peak shear strength of the soil seen in triaxial testing.

Core samples clearly took up ions readily over the 4-week soaking period and reached an equilibrium condition. This condition means either that ion exchange ceased when the ions in the solution were no longer able to overcome the thickness of the diffuse layer present on the surface of the clay, or that soil and solute are in an equilibrium with all negatively charged surfaces bonded with the K⁺ ions present in the solution (Wada, 1959). We conclude from this equilibrium situation that the solute concentration was adequate, and that tested samples would display any possible impact of salt manipulation.

Following treatment and triaxial testing, it is evident that the presence of K_2CO_3 within the soil cores has had an active effect on the shear strength of the soil with the shear strength raised across all three confining pressures that were used. We infer that the increased bonding associated with surface charge effects at elevated pH in an environment with abundant K^+ ions is the primary cause of the increased peak strength. Pore water pressures are relatively unaffected, indicating that the pore structure of the material is unchanged, and hence pore water pressure development is similar in the treated and untreated samples. Consequently, pore water pressure gradients are less able to break down the structure of the more strongly bonded materials.

6 CONCLUSIONS

Our studies suggest that mitigation of sensitive soil landslides through increasing peak strength using methods similar to those of Moum et al. (1970) and Helle et al. (2015) is a very real and plausible option for sensitive Bay of Plenty soils. Further studies into the effects of soil treatment need to be conducted across a wider range of confining pressures and treatment times, and the potential impacts of using such a method in practice on the environment and wider eco-system need to be investigated.

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