

EVOLUTION OF SHEAR STRENGTH OF CLAYEY SOILS IN A LANDSLIDE DUE TO ACID RAIN: A CASE STUDY IN THE AREA OF THREE GORGES, CHINA

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Abstract: Possible effects on landslide inception by acid rain induced changes in soil strength are investigated. Soil samples from freshly exposed slip surfaces and their immediate vicinity have been investigated at two landslides in the region of the Three Gorges, China. A visibly higher smectite content at the slip-surface and a dominant content of illite in the immediate vicinity are observed. In laboratory, remolded soils were subjected to acid water bath and tested for changes in their mineralogical composition and in their shear strength after the bath of different duration. The largest changes occur in the internal friction angle, which drops over one-third, concomitant with alteration of the originally smectitic soil with a substantial illite component into completely smectite dominated soil. Subsequently the friction rises again, simultaneously with neof ormation of kaolinite at the expense of the smectite component. Changes in cohesion are much less significant. The originally kaolinite-rich and illite-rich samples were found to be much more stable. A chemo-mechanical model of clayey soils is discussed.

INTRODUCTION

It has been believed for some time that weathering of some minerals, especially clays, may over time reduce the strength of soil and cause landslides. Seasonal changes of stability of slopes may be closely related to the content and type of clay in the slope, especially to the content of montmorillonite, the acidity of rain water in addition to the traditional factor of pore water pressure (Moore and Brunsd en, 1996; Jaboyedoff *et al.* 2004). Alteration of other clays into montmorillonite is a common stimulus to reduce the strength of slip surface (Shuzui 2001, 2002; Egashira and Gibo 1988). In addition, microstructure changes are often responsible for the strength change of deposited clay-rich soil (Moon, 1993). Finally, the loss of alkali-soil fraction caused by its interaction with even weak acid is also a factor (Hürlimann *et al.* 2001). Many slopes are at a meta-stable state, and a relatively minor change in their loading conditions is needed to bring them down. Equally, a minor change in the soil strength may cause the same result. We postulate that in Three Gorge area such a change is induced by acid rain.

Undoubtedly, there are many chemical processes that lead directly or indirectly to the reduction of shear strength of soils and hence landslides. We shall note the following hypotheses concerning the chemical changes induced by the rain water: the increase of soil acidity, decrease of salinity (and hence clay swelling), ensuing cation exchange, dissolution of essential minerals. So, the first part of this paper focuses on identifying mineralogical changes occurring in the field that could potentially lead to the reduction of soil strength. In the second part experimental results are reported performed on remolded soils subjected to acid water bath and tested for changes in their mineralogical composition and in their shear strength after different durations of bath. Several hypothetical mineralogical mechanisms are explored that might have affected shear

strength of the soils. Finally, the obtained results are discussed in the light of a chemo-plasticity model to allow to quantify and to build an operational prediction tool.

FIELD EVIDENCE

The field we investigated is located in the Three Gorges area in China. The Three Gorges region is located along the Yangtze River between the cities of Fengjie and Yichang in Chongqing municipality and Hubei province in the central China.

We present field evidence on samples collected from the slip surface (S) and close, but unaffected vicinity (V), of two landslides in the Three Gorges area: Qian-jiang-ping landslide (Q) and Diao-iao-zui landslide (D), which both occurred in June 2003 during an intense rainfall period. The objective is to identify mineralogical differences between these environments presumably linked to the causes of their different response to the rainfall. The rainwater in this area is highly acidic with pH value ranging between 3 and 6. The field evidence includes differences in groundwater composition.

The landslides took place across deposits of purple clay and were sampled from the intact slip surface and in the nearest vicinity. Sampling was performed 36 hours after the slide. The slip surface soil consists of quartz, feldspar, illite, smectite, mica, kaolinite, chlorite, limonite and magnetite. The smectite is mainly a calcium smectite, roughly expressed as $\text{Ca}_{0.24}\text{Na}_{0.01}\text{Mg}_x\text{Fe}_{0.02}\text{Al}_{1.75}\text{Si}_{3.87}\text{O}_{10}[(\text{OH})_2]_{1.978}\text{H}_2\text{O}$, where the fractional subscripts indicate the poor ordering of minerals in the slip surface.

Two independent methods were used to evaluate the difference in mineralogical composition: ultra-red spectrum and electronic probing micro-analyzer (EPMA).

Results of ultra-red spectrum provide a qualitative characterization of clay mineral composition of soils. The results are shown in Table 1.

Electronic probing allows one to quantify differences in chemical composition between slip surface and its neighborhood. Little variation of the major components, i.e. SiO_2 , Al_2O_3 , and Fe_2O_3 is seen. Percentagewise, much more significant are the differences in the content of oxides of Ca and Mg, which is higher, while that of K is lower at the slip surface compared to the vicinity. This is consistent with a claim that alkali components have been released during formation of the slip surface (Table 2).

Table 1. Mineral Content of the slip-surface soil revealed by ultra-red spectrum

Samples	Smectite	Illite	Kaolinite	α -quartz	Pyrite
D-S1	high	very low	undetectable	high	low
D-S3	high	low	very low	high	undetectable
D-V2	undetectable	high	negligible	high	low
D-V4	low	high	undetectable	high	low
Q-S5	high	low	low	high	undetectable
Q-V6	undetectable	high	low	high	low
Q-V7	undetectable	high	low	high	low

*D: Diao-jiao-zui landslide; Q: Qian-jiang-ping landslide; S: slip-surface; V: vicinity

Table 2. Composition of the slip-surface soil indicated by electronic probing micro-analyzer

Samples	Composition (%)					
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	CaO	MgO
Q-S	64.12	12.50	5.64	2.82	3.20	1.50
Q-V	62.55	13.72	6.10	4.25	0.31	0.95
D-S	64.10	11.50	5.75	2.10	2.59	2.77
D-V	61.51	15.30	7.70	4.34	0.60	0.52

Groundwater quality test

Groundwater quality data are of great interest as they allow one to determine components washed out from different locations. Samples #1 and #2 are respectively from the soil site above and below the slip surface of the Diao-jiao-zui landslide (Table 3). After filtration through the slip surface, the water changes from the #1 type of HCO₃⁻, Ca²⁺, K⁺+Na⁺ into the #2 type of K⁺+Na⁺, Ca²⁺, SO₄²⁻, HCO₃⁻. It is noted that water of the slip surface has a visibly higher content of the K⁺+Na⁺, that presumably has been released from clay.

Table 3. The quality of groundwater of Diao-jiao-zui landslide (D) area (mg/L)

Sample	pH	Ca ²⁺	Mg ²⁺	K ⁺ +Na ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	Free CO ₂	Erosive CO ₂
#1	7.5	73.60	3.53	58.42	30.18	55.73	274.50	10.56	2.8
#2	7.4	54.20	10.58	80.69	42.60	144.12	176.90	5.6	5.3

Discussion of the field evidence

The field evidence indicates a high content of smectite at the slip surface. However, illite is the main clay component in the vicinity. Besides, a significant potassium content appears in groundwater at the toe of the slope, possibly released from illite during the transformation. The excess of the smectite is attributed to the transformation from illite at the slip surface as it is not found elsewhere. No differences in color and grain composition or stratified deposition have been observed between slip surface and the vicinity. Furthermore, the ionic concentration of Ca²⁺ and Mg²⁺ are higher along the slip surface while that of K⁺ is lower, compared with that in the vicinity.

REMOLDED SOIL STUDIES

Experiments have been undertaken on an artificial soil in a simulated acid rain environment to investigate the relationship of the mineralogical changes to the shear strength evolution.

A total of 144 samples of clayey sand, with about 12% of clay, were taken at a water content of 23% on average. The composition of quartz sand is listed in Table 4. Three groups of soils were assembled using different clays: smectitic (11%), kaolinitic (12.5%) and illitic (13%) remolded with a weak solution of distilled water and HCL solution. The samples were subsequently exposed to a bath of an identical solution of HCl for duration of 1, 30, and 60 days, to simulate acid rain environments. Importantly, the same fluid was used for the bath and for the molding and compaction process to eliminate time lag of diffusion across the sample during the transient part of the chemical exchange between the sample and external bath solution. The

original pH of that solution was 3.45, corresponding to a relatively severe, but still realistic acid rain (Appelo and Postma 1989). The yearly average pH of rainfall is 5.44 in the Three Gorges region and its lowest monthly average is 3.75, while Yangtze River water pH is around 7.85-8.1 in this area (Yang *et al.* 2002). The samples were immersed in the bath immediately after their compaction. Subsequently, pH values for the solution and its concentration of ions were monitored over two months. The variation of the bath content in contact with the soil is listed in Table 5.

Table 4. Composition of the sandy mineral by X-ray diffraction

Sand	Mineral (%)										
	total clay	gypsum	analcime	quartz	orthoclase	plagioclase	calcite	dolomite	siderite	anhydrite	pyrite
	3.4	0	0	81.2	0	11.9	3.3	0.2	0	0	0

Table 5. Ion concentration of the solutions

Sample	Inundated Time (day)	pH	Conductivity (μ S)	K ⁺ +Na ⁺ mg/L	Ca ²⁺ mg/L	Mg ²⁺ mg/L	Cl ⁻ mg/L	HCO ₃ ⁻ mg/L	CO ₃ ²⁻ mg/L
#1	Original liquid	3.45	5.6	/	/	/	/	/	/
#2	1	6.3	42.6	28.52	6.40	1.94	21.27	6.10	0
#3	30	7.21	128.3	60.85	14.40	5.35	49.63	9.76	0
#4	60	7.75	174.5	414.76	81.22	23.58	311.99	53.69	0

After the prescribed period of the acid bath, samples were tested in direct shear apparatus at a shearing rate of 2.4 mm/min to determine c' and ϕ' , i.e. effective cohesion and internal friction angle, averaged from four tests on each batch of bath duration.

Clay mineral composition was determined via X-Ray diffraction analysis for each duration of the bath. The results are listed in Table 6. In the same Table the Smectite “Crystallinity” Index, S is reported.

Before discussing the resulting relationships it needs to be clarified that the experimental set-up simulates the field conditions under the following premises. Initially, the sample pores and the bath container were filled with the same acidic water. This corresponds to a situation where very low pH rainwater inundates soil pores. In reality, the ground water is not distilled de-aired water. It is observed that the acidity of the bath container decreases clearly and consistently in time from 3.45 to 7.75 in two months. As the initial pH is equal, both in soil and solution, the driving force must be something else other than pure pH effect. It is speculated that the change in pH in the solution is accompanied by the change in acidity soil.

It is not known what causes the observed changes in strength, and possibly the resulting destabilization of landslides. We shall note the following hypotheses: smectitization of illite, decrease of salinity due to rainfall and hence clay swelling, directly the increase of acidity, ensuing cation exchange, dissolution of essential minerals. Some of these processes are known to play a buffering role for pH effect, as dissolution of gibbsite $Al(OH)_3$, ion exchange and

weathering of primary silicates (see e.g. Appelo and Postma 1999). It is observed that soil releases substantial amounts of K^+ and Na^+ ions and to a lesser degree of Ca^{2+} .

After the differentiated exposure to acidic conditions the clays were subjected to direct shear tests in a shear box. Values of cohesion and friction angle were recovered after 1 day, 30 days and 60 days of bath, and are shown in Fig. 1.

Table 6. Relationship between mineral compositions, smectite “crystallinity” index and shear strength parameters

Sample	Clay type and quantities (%)							S%	c'	ϕ'
	I	I/S	C/S	S/I	S	K	C [#]			
S*	/	/	/	/	73	27	/	/	/	/
RS-1☒	23	/	/	55	/	11	11	70	23.62	29.28
RS-30☒	15	/	/	/	68	11	6	10	40.14	20.53
RS-60☒	24	/	/	8	/	58	10	65	25.49	27.10
K †	12	8	/	/	/	80	/	10	/	/
RK-1★	20	/	/	63	/	9	8	70	3.22	31.68
RK-30★	26	/	/	/	/	74	/	/	9.03	30.83
RK-60★	26	5	/	/	/	69	/	10	5.95	33.25
I*	82	/	/	/	/	/	18	/	/	/
RI-1☉	/	/	/	/	/	/	/	/	21.21	29.40
RI-30☉	8	3	/	/	/	/	9	10	17.56	29.35
RI-60☉	6	25	/	/	/	/	9	10	23.50	30.95

*S: Smectite; ☒RS-1, RS-30, RS-60: smectite remolded soil inundated one day, 30 days, 60 days respectively

†K: Kaolinite; ★RK-1, RK-30, RK-60: kaolinite remolded soil inundated one day, 30 days, 60 days respectively

*I: Illite; ☉RI-1, RI-30, RI-60: illite remolded soil inundated one day, 30 days, 60 days respectively

#C: Chlorite

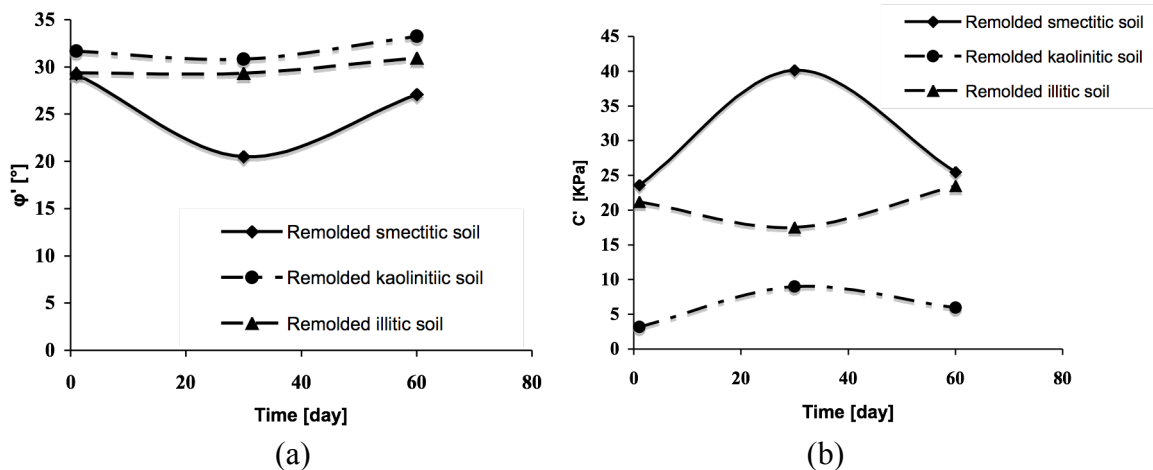


Figure 1. Evolution of (a) internal friction angle (b) cohesion on effective stress basis

Analysis

The testing of the soil strength reveals a substantial evolution of strength with time after immersion in acidic bath. Unfortunately, no data are available on the original specimens

immediately after the acid-water permeation. The earliest data points refer to the one-day old bath, when it is believed there are no pH gradients across the specimen. The obtained results lead to the following conclusions:

- Evolution of both the internal friction angle and cohesion is non monotonic with time in all three soils.
- ***In the original smectitic soil the evolution is substantial***, and much less so in the original kaolinitic and illitic soils.
- The internal friction angle of smectite and kaolinite first increase (30 days) and then decrease (60 days), It remains almost unchanged in the illitic soil.
- Cohesion of the originally smectitic and originally kaolinitic soil first increases (30 days) and then decreases (60 days), while in the originally illitic an opposite trend is observed: cohesion first decreases and then reverses to the value in smectite.
- ***The key changes appear to be those in the originally smectitic soils in terms of the evolution of Coulomb shear strength***. As the Coulomb strength is a linear combination of cohesion and the internal friction coefficient times the normal stress, its evolution has a different outcome depending on the normal stress. The failure locus for the originally smectitic soil is shown in Fig. 2d. Smectitic soil shear strength decreases 26% within the first 30 days for normal stress of 500 kPa, while it slightly increases below the normal stress below 100 kPa, in the same period. However, the latter change is quite limited. The evolution of illitic and kaolinitic soils in terms of their strength is very limited.
- Correlations between the change in cohesion and friction angle and Smectite Crystallinity Index S [%] are monotonic and nearly linear. Cohesion decreases, while the friction angle increases with S . Smectite Crystallinity Index is defined for interstratified illite/smectite minerals whose layers are regularly distributed, as the ratio of the number of layers of smectite to the number of total layers. (Gruner 1934; Weaver 1956) For an interstratified illite/smectite mineral distributed irregularly, no such ratio is defined.
- As we are interested in the conditions of the weakening of soil, it is immediate to see that these conditions arise in a brief period of time (less than 30 days) after the incursion of the highly acidic water, and above the normal stress of 100 kPa in originally smectitic soils. Notably, such conditions disappear between 30 and 60 days.

The data on smectitic soil evolution in Table 6 suggest that this soil evolves from predominantly interstratified Smectite/Illite (55%) with some illite (23%) at one day of bath, to predominantly smectitic (68%) at 30 days, to predominantly kaolinitic (58%) at 60 days of bath. The percentages are referred to the initial clay fraction. The soil composition at the onset of bath is not available. Based on a generic assessment (Mitchell and Soga, 2005), S/I clays are considered as relatively strong, compared to smectitic clays, which are definitely weak, but definitely not as strong as kaolinite.

Finally, micrographic evidence indicates an evolution of the material structure during exposure to acidic pore fluid. The one-day exposed sample exhibits relatively low porosity and a presence of a flaky illite/smectite intergrade forming thick walled diaphragms between the grains of sand and silt. A 30-day exposed sample exhibits relatively small ($1\mu\text{m}$) 3-D clusters of smectite filling most pores between the silt and sand particles. Finally, a 60-day sample presents a massive presence of relatively large particles of kaolinite bridging between sand particles. (See Figure 2a, b, c)

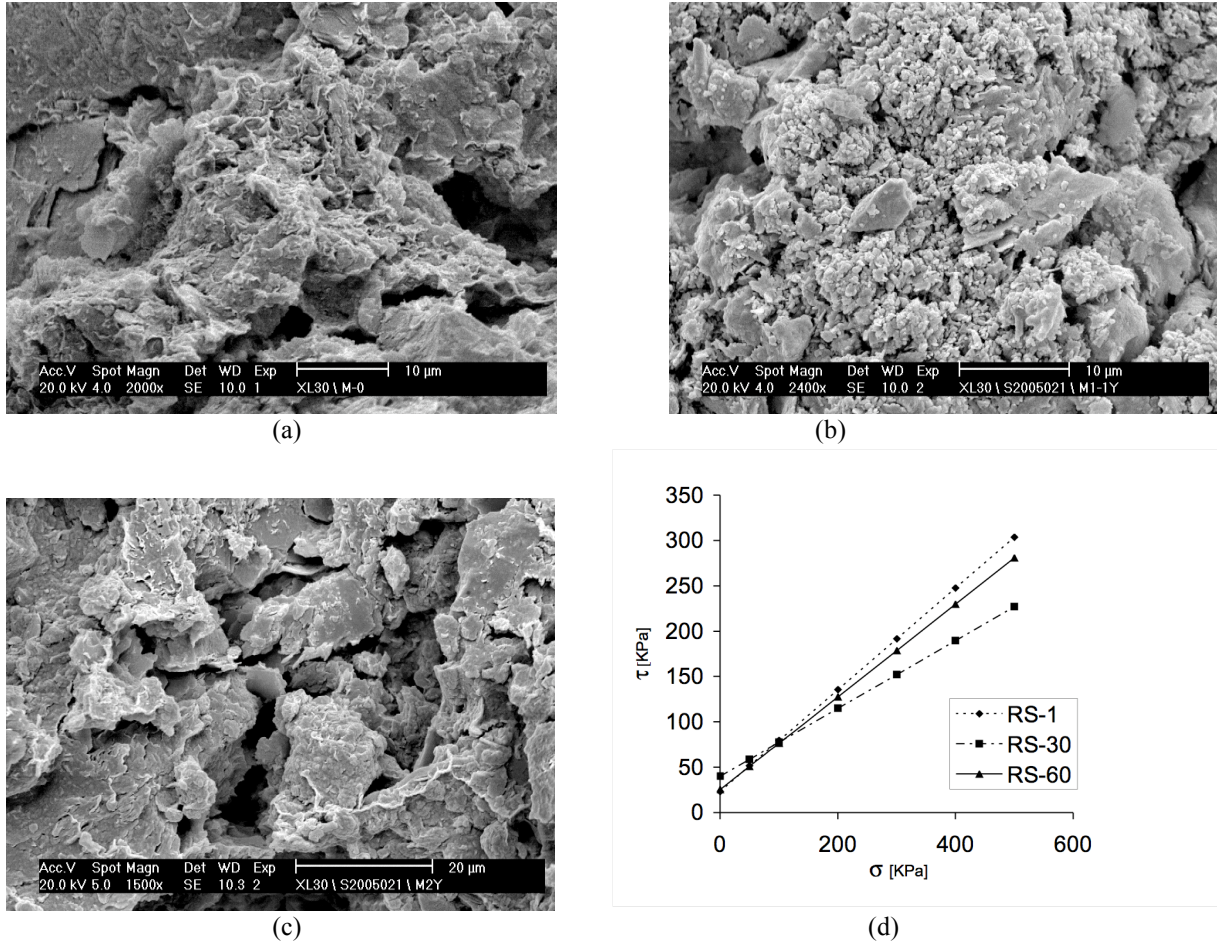
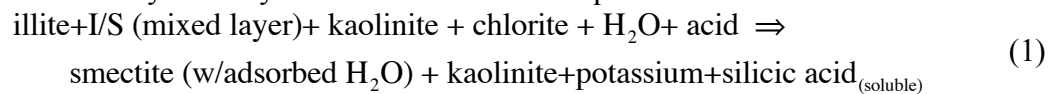


Figure 2. Evolution of smectite remolded soil soaked, (a) 1 day by SEM ($\times 2000$), (b) 30 days by SEM ($\times 2000$), (c) 60 days, by SEM ($\times 2000$). (d) Mohr-Coulomb failure envelopes on Day 1, 30 and 60.

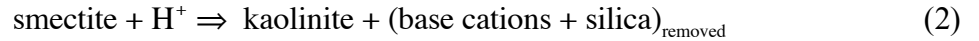
On the basis of the above evidence the following scenario of mineral evolution at the landslide site is proposed.

- The infiltration of acidic rainwater triggers a principal mineral evolution process of smectitization of illite. The illite in question is part of the S/I mixed layer. The field evidence of the comparison between the mineral composition of the slide-surface and vicinity seem to confirm this hypothesis. Additional field support comes from the presence of potassium most possibly released into the groundwater during alteration of illite into smectite. The proposed process appears to take place in a period of nearly 30 days in the acidic bath experiment on remolded material as evidenced by the increase in smectite component replacing the interstratified S/I in the soil samples and its dramatic drop in Smectite ‘Crystallinity’ Index. The reaction in question is



The effect of a significant increase in pH in the solution of the bath may indeed suggest a buffering effect triggered by dissolution of illite accompanied by an intense cation exchange activity.

- Two questions remain open in respect to the above part of the process: first, what is the support of the concept that the alteration occurs as a result of a single episode of acid rain and, second, why does it takes place at a localized site. The rate of the process in the experiment suggests that it is possible for the alteration to occur in a period of a few weeks. This is also confirmed by previous studies (see e.g. Brinkman 1976). Vast landslide survey data invariably point to the rainfall inflow via localized zones of prior fracturation at the slope crest of either mechanical or erosional origins. Such localized fracture zones supply a larger than average (regional) flux of water and hence acid into the ground, at the expense of the surface runoff water flux. This is what leads to a localized higher concentration of acids, and hence a locally more advanced alteration of clays.
- The scenario also predicts that at a particular condition (occurring after about 30 days) alteration of I/S to smectite becomes replaced or dominated by a reaction of neoformation of kaolinite on the basis of the previously produced smectite. This reaction takes place, if there is a supply of H^+ , whereas the base cations and silica are leached out or precipitated. The reaction is (see e.g. McBride 1994)



However, whenever the soluble products increase in their concentration in the solution, then a reverse reaction may start reforming smectite and equilibrium may soon be reached. It is to be kept in mind that the dissolution of smectite could continue as long as the pore water is undersaturated by smectite. In the environment of a landslide caused by a rainfall the continuation of dissolution of smectite, or neoformation of the kaolinite will depend on the drainage conditions. An *in situ* investigation of groundwater at a depth of about 2m in a tropical rainforest at a muscovite soil horizon reveals a significant neoformation of kaolinite in a later phase of the event (past 1200 hours) (Grimaldi et al. 2004).

In the presented experiment on the remolded material, conducted in a closed system, vigorous stirring was performed that presumably enhanced removal of products from the samples. Given that, it can be justified that neoformation of kaolinite did take place, as suggested by the mineralogical composition after the bath of 60 days (Table 6).

Modeling

Modeling proposed for the strength change during chemical reactions follows the template outlined by Hueckel (1992, 2002) and Hu and Hueckel (2006), in which the yield condition is made explicitly dependent on the variables of the progress of reaction. In our specific case, the yield condition is expressed as

$$f = \tau - c'(\varepsilon_q^p, \xi_{sm}, \xi_{ill}, \xi_{kao}) - \sigma'_n \tan \phi'(\varepsilon_q^p, \xi_{sm}, \xi_{ill}, \xi_{kao}) \quad (3)$$

where τ, σ'_n are the shear and normal effective stress components at a yielding plane, whereas c' and ϕ' are effective cohesion and friction angle. $\varepsilon_q^p, \xi_{sm}, \xi_{ill}, \xi_{kao}$ are plastic shear strain, and variables of the accumulated relative mass removal during smectitization and kaolinitization respectively; the latter ones varying between 0 and 1.

The two variables of the accumulated relative mass removal during illite dissolution and smectite dissolution are expressed as, respectively

$$\xi_{ill} = -\frac{\Delta M_{ill}}{M_{total}}; \xi_{sm} = -\frac{\Delta M_{sm}}{M_{total}}, \xi_{kao} = -\frac{\Delta M_{kao}}{M_{total}} \quad (4)$$

The variables of mass change ξ_i , $i = ill(ite)$, $sm(ectite)$ and $kao(linite)$ in the yield limit are the result of the time integrals of the respective reaction rates. However, the expressions of rates are also functions of pH . The variation of $pH(x,t)$ is controlled by solution of the boundary value problem of transport (both diffusive and advective) of acids. Clearly, such a boundary value problem may be differently formulated, but this is beyond the scope of this paper. Both factors: reactive and diffusive, induce a rate dependence in the chemo-plastic formulation. The nature of the rate processes and their dependence on the conditions of reactions, such as open system condition of neof ormation of kaolinite, imposes an additional degree of history (geochemical) dependence to the behavior, and hence the chemo-plasticity model.

The assessment of the rates of reaction such as dissolution of illite is far from being well understood. There are no specific data on the rates of the reactions in soils from the locations of the Three Gorges' region. Kohler *et al.* (2002) have established empirically an "apparent" rate of dissolution of illite in acidic environment, based on the amount of dissolved silica in the pore water in a closed system experiment.

The observed dependence of dissolution rate on pH revealed is quite strong: at $pH = 2$ the rates are of the order of 10^{-13} , at $pH=7$, 10^{-15} , and at $pH = 12$, back to $10^{-13.5}$ mol/ (m² sec). However, by the nature of these measurements, as their authors point out, the rates are inclusive of possible precipitation of secondary phases. These secondary phases include smectites. No parallel experiments in open systems were performed, in which the potential precipitates would be washed out. There seems to be no data available that would specify the rate of dissolution of illite and precipitation of smectite for the same material. For that reason the strength variation should at this stage be related to the mass loss of illite on the one hand and to the change in specific surface area variations measured by adsorption methods that can access the interlayer space in smectites.

As for the neof ormation of kaolinite, its kinetic is linked to dissolution of the altered smectite. The rate of dissolution of smectite is known to decrease with pH from $10^{-10.5}$ at $pH = 1.5$ to $10^{-10.5}$ mol/g.sec at $pH = 4.5$ (Amram and Ganor 2005). The rate of kaolinite precipitation (Nagy and Lasaga 1993) at $pH = 3$ is at 10^{-12} mol/ (m² sec).

A simple plasticity model based on smectite, illite and kaolinite mass removal could be proposed as follows. The friction angle is proposed to be linearly dependent on ξ_{sm} , ξ_{ill} and ξ_{kao} , $\phi' = \vartheta_{sm}(m_{sm}^0 - \xi_{sm}) + \vartheta_{ill}(m_{ill}^0 - \xi_{ill}) + \vartheta_{kao}(m_{kao}^0 - \xi_{kao})$. ϑ_{sm} , ϑ_{ill} , ϑ_{kao} are material constants that represent the linear dependence of the effective friction angle on smectite, illite and kaolinite content respectively. The clay contents of smectite, illite and kaolinite, of Day 1 in Table 6 are chosen as those for the initial state, m_{sm}^0 , m_{ill}^0 and m_{kao}^0 . The relative mass removals for the two other states at Day 30 and 60 are calculated with respect to this initial state. An additional state is introduced, that when there is no component for either of smectite, illite and kaolinite content, the friction angle becomes zero. Hence three algebraic equations could be obtained regarding the three coefficients in the function. Solving this equation system gives $\phi' = 29.28 - 109.72\xi_{sm} - 456.15\xi_{ill} - 396.37\xi_{kao}$. Similarly, the internal cohesion could be expressed as $c' = 23.62 - 485.01\xi_{sm} + 280.04\xi_{ill} - 357.3408\xi_{kao}$.

CONCLUSIONS

The field data suggest that at the location of landslides, illites or mixed layer I/S of indigenous slopes were altered into smectite and subsequently kaolinite neof ormed from that transitory

smectite. The experimental simulation of the remolded soils and the imposed change in acidity of pore water support that course of reaction. The experiments reveal also a complex pattern of strength change with time. The central feature is the variability in the internal friction angle, which decreases over one-third upon alteration of illite into smectite followed by an increase over a similar value upon neoformation of kaolinite. Evolution of cohesion, which has an opposite trend, appears to bear less influence on the evolution of strength in the range of normal stress of relevance to slope stability. Interestingly, it appears that the reduction of strength occurs during first 30 days after the acidification of pore water, while after that time the process reverses. This finding however, ignores all effects of retardation of the process due to acid transport phenomena.

A simulation of the slope stability in the presence of destabilizing chemical conditions is a coupled chemo-mechanical problem. In addition to mathematical models for soil mechanics and geochemistry it requires the terms of coupling. This paper provides a rudimentary tool for coupling of mechanical behavior to chemical variables. However, the other side of the problem, which is the dependence of chemical behavior on the deformational part remains unaddressed. Indeed, not all parts of geochemical modeling are known, especially related to the conditions of the two-step reaction of alteration of illite into smectite followed by the dissolution of the latter and neoformation of kaolinite.

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