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## Wastewater disposal and problem soils in Lanzhou, China

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LANZHOU CITY is the capital city of Gansu Province, PR China. The city is built on the relatively level Huang He (Yellow River) terraces at an altitude of about 1500m and has an estimated population of about two million. The region is characterized by a hilly to mountainous environment where an undulating bedrock relief is covered by a semi-continuous drape of Quaternary silty aeolian deposits called loess. These loess deposits are subdivided into four stratigraphical units comprising the Wucheng loess (Early to Middle Pleistocene), the Lishi loess (Middle Pleistocene), the Malan loess (Late Pleistocene) and a thin Holocene loess layer (see a.o. Billard *et al.* 1993; Derbyshire *et al.* 1993; Liu and Chang 1964). These loess deposits may reach thicknesses of more than 300m. Malan loess deposits cover extensive parts of the Huang He river terraces and frequently small scale failures in these loess deposits occur within the boundaries of the city.

The region is characterized by an arid to semi-arid climate with annual precipitation rates of 200 to 500mm and a potential evaporation of about 1500mm/yr. As a consequence the ambient field moisture content of the loess deposits are only partially saturated characterized by moisture contents as low as 8 to 10%. These low moisture contents are essential for maintaining the loess structure which consists of a framework of silt sized particles (predominantly quartz and some feldspars) being supported by a cemented network of clay-sized particles forming bridges and coatings. The presence of cementation determines to a large extent the structural strength of the deposits. The brittle cementation bonding is a function of the availability of calcium carbonates and, to a limited degree, also soluble salts may contribute to this brittle cement. Clay minerals can play an important role in forming ductile bonds dispersed through the openwork fabric of loess. However, the clay mineral content of the non-weathered aeolian loess is low and

under low partial saturation loess fails in a brittle mode. On average, Malan loess contains about 11% calcium carbonates, while in the Wucheng loess it may be as high as 16%. For the Malan loess its open work structure has characteristic void ratios greater than 1.0 (indicating that the volume of voids is larger than the volume of solids). The occurrence of the widespread carbonate cementation gives the loess its high structural strength which can be summarized by using the effective cohesion and internal friction angles for the undisturbed samples of 30 kPa and 26° for the Malan loess, 54 kPa and 30° for the Lishi loess, and 52 kPa and 35° for the Wucheng loess (Table 1; see Derbyshire *et al.* 1993, 1994; Dijkstra *et al.* 1994, and Wang *et al.* 1991).

The highest mountains around Lanzhou city reach heights of 2600 to 2900m generally having long steep slopes characterized by a relative relief ranging from 200 to more than 500 metres and slope angles as high as 45°. Expansion of the city is thus severely limited. A current need for more space for industrial and urban expansion of the city, intensified by the greater attention the central government in Beijing is paying to formerly 'marginal zones', has led to extensive levelling activities just north of the city in the valley of the Luo Guo Gou in order to create space for the establishment of new industry and some housing. However, much still depends on an increase in housing density in certain areas of the city and the utilisation of steep, potentially unstable escarpments of the river terrace edges and the lower slopes of the loess-covered surrounding hills where the houses are built on man-made terraces dug into the loess deposits. The nature of these loess deposits allows for the creation of caves which are used for storage or even housing of entire families. Slope stability is, of course, severely affected by the digging of these caves. However, another, arguably more important, factor is the way in which the local households have to dispose of their wastewater.

Table 1. Some representative properties of Malan loess samples

TO PASTE
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s.g. = specific gravity; r. = bulk density; m.c. = moisture content;  $e_0$  = void ratio; n = porosity; LL = liquid limit; PL = plastic limit; PI = plasticity index, c = cohesion,  $\delta$  = internal friction angle.

Although the city is situated in an arid to semi-arid environment sufficient water can be used from the Huang He and from water bearing strata to the north of the city. At present there is a continuous water supply to the majority of the suburbs of Lanzhou. However, facilities for the disposal of waste water are far from adequate in most parts of these suburbs and waste water disposal frequently occurs by letting it drain away into the loess, directly adjacent to the houses. Although part of this water will rapidly evaporate during the warm summer months, sufficient amounts of water slowly seep through the loess deposits causing a gradual destruction of the loess fabric and a decrease of the structural strength. Where a waste water drainage infrastructure is available poor maintenance combined with frequent small scale slope movements has led to numerous leaks in this systems. At these sites rapid disintegration of the loess fabric occurs, followed by piping or even mass failure of the slopes.

In the next section, the effects of water on loess strength will be discussed followed by an assessment of changing slope stability conditions of a slope in Malan loess within the city limits of Lanzhou.

As an example of the impact of human activity on slope instability conditions within the city of Lanzhou a landslide near Baita Park will be discussed. This landslide took place in one of the densely populated suburbs of Lanzhou city on the 9th of November 1986 and, despite its limited size, caused the death of seven people and the destruction of several houses. A dispute has arisen about who should be held responsible for the initiation of the slope failure. On the one hand, movement may have been initiated by extensive weathering of the loess caused by seepage of waste water sewage from the houses on the higher slopes of the terrace. Alternatively, slope stability may have been reduced sufficiently by uncontrolled excavation activities at the base of the slopes (including local oversteepening of the slope and the construction of a loess cave for storage purposes). The stability analysis presented here does not settle this question and merely illustrates the results of the geotechnical testing in relation to the increased moisture content and the potential effects of a long term throughflow at this site. The Baita Shan profile has been selected for three reasons. First, reliable data are available for the reconstruction of both the pre- and the post-failure profiles. Second, the slope is representative of large areas of terrace edge in the built-up area of Lanzhou, and the instability of such slopes is known to cause extensive damage to properties and to threaten lives and livelihoods in this densely populated area. Third, because the slope is homogeneous it is unlikely that internal anisotropy (such as palaeosols or changes in the type of loess) predetermines the location of failure surfaces, or that a build-up of a ground water table will occur within the slide mass. A number of field observations indicate that progressive failure of these slopes is a common phenomenon. These indicators include: extensive cracking of the upper slopes; salt efflorescences at spring zones; localized subsidence on the terrace levels associated with the collapse of the loess fabric which, in the case of Malan loess, may amount to

a linear decrease as much as 15%; and steps in the terrain associated with large scale creep along potential failure planes (cf. CSCCC 1978 and Dijkstra *et al.* 1994).

The variations in loess structural strength derived from extensive geotechnical testing in the laboratory and *in situ* can be used to assess the effects of progressive weathering and varying moisture contents on the failure of loess slopes in Gansu Province. The changes in slope stability at this site are presented below using slope stability analyses for a range of "weathering stages" which are thought to represent the effects of progressive weathering of the loess deposits at this site comprising the dissolving of the readily soluble components of the loess fabric and the effects of changing pore pressures.

When tested under low normal stresses, peak strength conditions of the Malan loess are frequently observed. However, at higher normal stresses this peak strength condition tends not to develop and failure of the sample is characterized by strain hardening resulting of the plastic deformation in the shear zone, whereby the fabric is changing as a result of a rearrangement of the particles. Subsequently, the more effective particle interlocking induces a slight increase in the effective angle of internal friction.

A large difference exists between undisturbed Malan loess (characterised by an extreme openwork fabric), and the same sample after shearing. The development of a more compact fabric, stress anisotropy, and discontinuous shear zones severely alter the behaviour of this type of loess. Permeability values, collapsibility coefficients and void ratios decrease sharply.

A set of samples, derived from those used for the undisturbed loess tests, was used to remoulded manually and tested in a modified Bromhead ring shear apparatus (see Bromhead 1979 and Boyce *et al.* 1988). The tests were carried out to assess the effects of changing moisture contents on effective (apparent) cohesion and effective angle of internal friction. It was found that the apparent cohesion gradually increases to a value which is about 40 to 50% of the effective cohesion values of the undisturbed samples tested at their unaltered field mois-

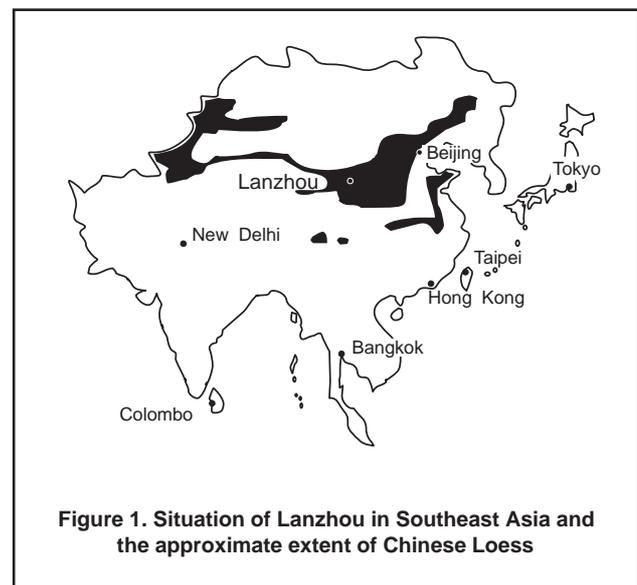


Figure 1. Situation of Lanzhou in Southeast Asia and the approximate extent of Chinese Loess

**Table 2. Malan loess strength data used for the slope stability analyses of Baita Shan**

Weathering percentage (WP) is the degree to which a slice has been affected by weathering.

ture content of around 7%. When the moisture content of the remoulded samples exceeded a threshold value of about 18 to 20%, a sudden decrease was noted in the effective cohesion as well as an increase in the scatter of the data occurs. The effective angle of internal friction indicates that the gradual increase in the thickness of the water membranes surrounding the particles plays an important role in the increase of the internal friction angle in the moisture content trajectory between 2 and 5%. At moisture contents greater than 5% a gradual decrease of the effective internal friction angle is noted, with again a greater scatter of the data occurring at moisture content values exceeding 18 to 20% which are just exceeding the plastic limit and are representative of saturation degrees in excess of 0.95.

Slope stability analysis was carried out using a limiting equilibrium method of slices following the method of Sarma (see *e.g.* Sarma 1973, 1979). In our example the slope mass was divided into 14 slices. Three separate calculation series were used to simulate stepwise internal weathering along the known critical slip surface from totally undisturbed to fully remoulded and weathered (see Figure 2). In these series of calculations weathering was assumed to take place either from the top or from the toe of the slope. In the third series weathering was assumed to progress alternately from the toe of the slope and from the top of the slope. Based on the data obtained from the geotechnical tests of both the undisturbed and manually remoulded samples, an array of strength characteristics was constructed and used as a surrogate for the various stages simulating progressive weathering in loess (Table 2). According to these data the hypothetical progressive weathering is simulated by changing the  $c'$  and  $\tan \phi'$  values from peak values into remoulded values for one or more of the fourteen slices. It is assumed that each slice behind the 'weathering front' is in a remoulded state and undergoes a progressive increase in moisture content (5, 10, 15 and 20%). Additionally, it is assumed that the sliding body is dry (moisture content not exceeding 5%), and that near-saturation conditions occur only at the slip surface. The results of the analysis

are expressed as the equivalent percentages ( $eq$ ) of the total slip surface length influenced by weathering. For this purpose the weathering percentages are used as mentioned above and described in Table 2. Typically, the weathering situation at any time was defined with the following relationship:

$$eq = a + 0.75b + 0.5c + 0.25d \quad (1)$$

where

$a$  = percentage of the (remoulded) slip surface at 5% moisture content ( $x_2$ )

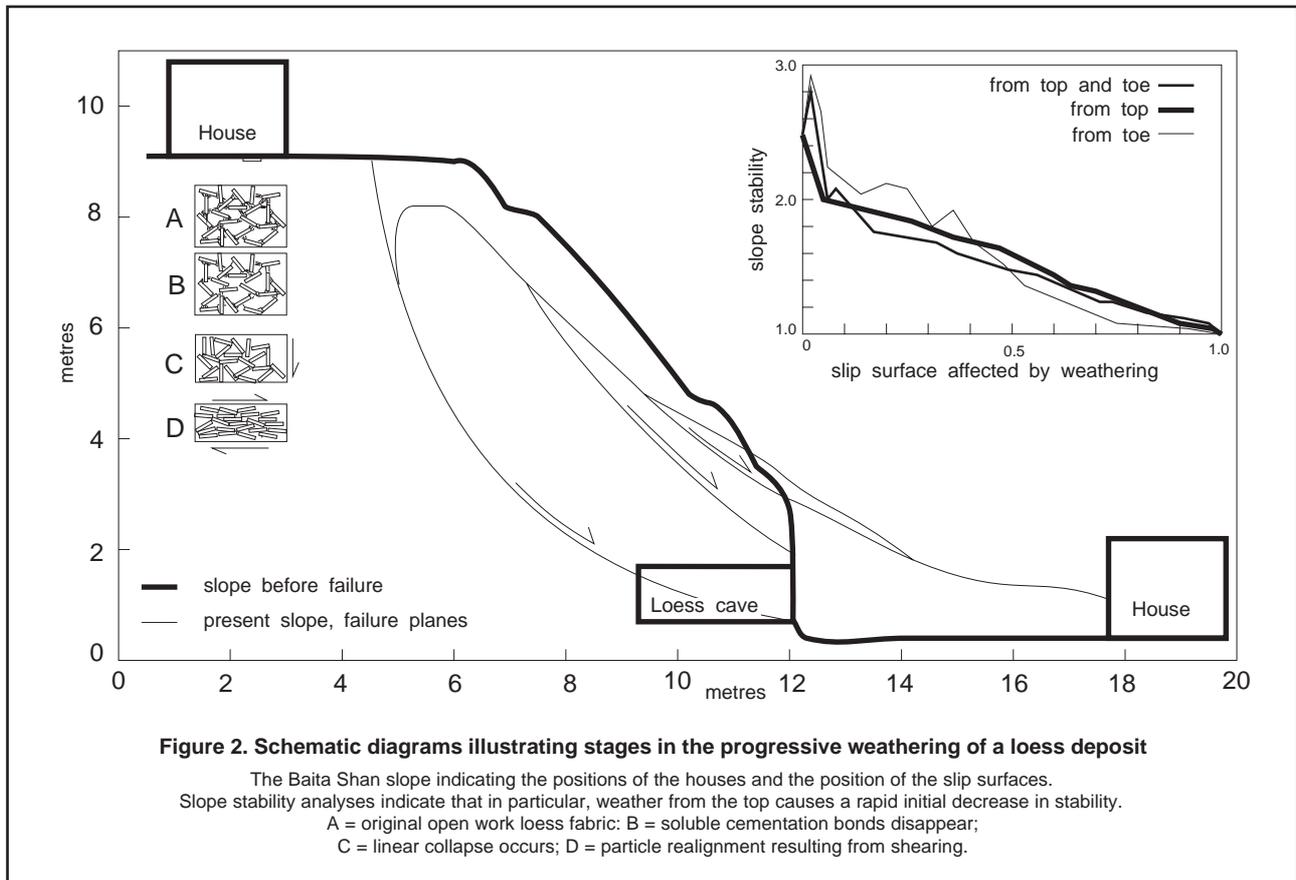
$b$  = percentage of the (remoulded) slip surface at 10% moisture content ( $x_3$ )

$c$  = percentage of the (remoulded) slip surface at 15% moisture content ( $x_4$ )

$d$  = percentage of the (remoulded) slip surface at 20% moisture content ( $x_5$ )

The results of the analyses are shown in Figure 2. With the weathering from the top of the slope a strong initial decrease of slope stability occurs, which is explained by the considerable drop in effective cohesion values when the loess changes from an undisturbed into a weathered ('remoulded') state and the relatively small effective normal stress acting on the failure plane at this point. This effect gradually becomes less important with the increase in the effective internal friction angle taking effect at greater depths after further progression of the internal weathering of the slope. Slope stability analyses carried out while adding weathered slices from the toe of the slope indicate an initial increase in factor of safety due to the higher internal friction angles of the weathered slices causing the lowest slices to act as buttresses against movement of the upper parts of the slopes. After adding the third slice this effect is diminished by the changes in the effective apparent cohesion values, leading to a sudden drop in the safety factor. This curve does not follow the relatively smooth progression of weathering from the top, but for certain additional slices the factor of safety increases above the previous value. The reasons for this are thought to be a combination of the complexity of strength parameter variation ( $c'$  falls, rises and then falls again while  $\tan \phi'$  rises then falls), the irregular pre-failure surface profile and the considerable influence of effective normal stress up to at least 50% weathering, and the rapid inclination of the failure plane.

During the simulation of the combined effects of weathering of the top and the toe of the slope an initial increase in factor of safety is observed, which is immediately followed by a rapid decrease and a subsequent small increase. Both increases are caused by the higher values of the effective internal friction angle of the remoulded loess. These higher values are particularly effective in the lower part of the slide, where the effective internal friction angles are significantly higher than the local slip surface angle measured at the base of each slice and the effective normal stress is greatest. The effect will be even more pronounced for larger mass movements where the changes in effective internal friction become relatively more important than the changes in effective



cohesion. Figure 2 indicates that slopes which, in an unweathered state, have safety factors close to unity might fail after only a short period of progressive weathering. This process will take considerably longer for the initially more stable slopes. Within the urban environment the man-made cut slopes are frequently close to equilibrium and therefore moderate amounts of weathering affected by e.g. the uncontrolled disposal of waste water may bear great risks for these sites.

The following conclusions may be drawn from the results and discussion presented here.

1. The youngest (Malan) loess has a peak strength at low normal effective stresses but fails plastically at normal effective stresses above approximately 100 kPa. The older (Lishi and Wucheng) loesses exhibit greater strength and brittle failure because they are cemented.

2. The behaviour of the remoulded loess is markedly different showing higher effective internal friction angles and lower effective cohesion values. The change in the effective angle of internal friction is caused by the redistribution of the particles into a denser packing; the loss of cohesion is caused by the breaking up of the cementation bonds.

3. Weathering of loess, for example by dissolution of the cementing bonds, results initially in structural collapse and a consequent large increase in effective angle of friction and reduction in effective apparent cohesion.

4. As the water content of the remoulded loess rises, the effective apparent cohesion rises proportionately for all three loess types up to a limiting value of approximately 20 kPa at a water content of 16 - 18%, after which the

value falls rapidly to a much lower, somewhat variable level.

5. The effective angle of internal friction rises to a maximum at a water content of approximately 5% and thereafter falls to a lower value at approximately 20%, whereupon the effective strength parameters stabilise since the soil becomes completely saturated.

6. Progressive weathering from the top of the loess slopes causes a dramatic reduction in their stability, whereas progressive weathering from the base results initially in stabilisation of these relatively large slopes because on collapse of the loess structure of these Malan loess deposits a rise in the effective internal friction angle occurs. Detrimental effects only occur once the weathering has progressed beyond a certain stage.

7. The processes described above are not only related to loess soils, but are representative of a wide range of cemented and/or collapsible soils which cover large parts of the globe. Occurring predominantly in arid to semi-arid zones these soils maintain their open structure under low moisture contents and are therefore extremely sensitive to changes in their internal hydrological regimes. Particularly in an urban environment relatively small scale hazards bear a great risk and have a profound impact on human activities.

This paper presents some of the results taken from a much larger study of landslides and mass flowage in the loess of north-central China supported by the Council of the European Communities and the Government of Gansu Province, P.R. China and carried out in 1987-1993. Special acknowledgements are due to my Chinese research

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