6 Special aspects of interaction

6.1 Mutual benefits by modelling soil and structure within the same mechanical approach (*H. Hartl*)

6.1.1 Abstract

This section shows an illustrative example of how interaction problems between structural and geotechnical engineering are faced in the Austrian educational system. The structural behaviour of a pile wall for securing an unstable slope was investigated. Although the study was carried out at the Institute for Soil Mechanics and Foundation Engineering the performance of the reinforced concrete piles was investigated as well. It could be shown that the head deformations of the piles increase significantly if the concrete starts to crack.

6.1.2 Introduction

The goal of the Austrian civil engineering system is to give a broad spectrum of knowledge to the students. This ensures a high level of understanding between the several civil engineering professions, in this case between the structural and geotechnical engineer. The problem presented here (Hartl, 1997) was elaborated within the course 'Project in Geotechnical Engineering' under the careful advice of Dr Roman Marte, who has conducted research in the area of soil structure interaction (Marte, 1998). The students can take this elective course shortly before starting their diploma thesis. The course expounds a project that shows the interaction of several fields of expertise, in contrast with the final diploma thesis, which usually concentrates on one specific problem in one field of expertise. The project presented here, was carried out by the present author whilst at university.

6.1.3 Problem investigated

The unstable slope shown in **Figure 6.1** is a real field problem. A soft soil layer with a thickness of approximately 10 m is sliding on a rock mass that has fairly good mechanical parameters. Two ways to guarantee the safety of the slope appear to be available: either using a spaced pile wall with drilled piles, or building an excavated shaft foundation with an elliptical shape. During the excavation process the slope would be saved temporarily with shotcrete until finally the excavation would be filled with reinforced concrete.

6.1.3.1 Soil parameters

The most important parameters employed are shown in **Figure 6.1**. In general, soil parameters are difficult to determine so analyses using various measurements and a continuous checking process are recommended. Fortunately, in this case the parameters for the slope are well known. Footings (shaft foundations) for a highway bridge are situated at this specific slope. The required parameters were determined with care for the bridge footing and then verified from measurements taken during construction of the footing.

6.1.3.2 Concrete parameters

Reliable concrete parameters for the analysis are much easier to obtain, since the designer can specify a certain class of concrete and the contractor should ensure that the concrete develops the required parameters. However, the moment–curvature performance of the reinforced concrete pile can be very unpredictable for some levels of loading; this is discussed below.

6.1.4 Performance of a reinforced concrete pile embedded in soil

It can be seen in **Figure 6.2** that the deformation of a concrete pile can be split into two parts. The first is a rigid body motion (translation and rotation) that causes no internal forces on the concrete pile. The second is an internal deformation of the reinforced concrete pile caused by forces acting on the concrete. Since this internal deformation cannot be neglected (unlike the rigid body motion), adequate stiffness of the concrete pile is essential.

6.1.4.1 Stiffness of the reinforced concrete pile

Figure 6.3 shows a generic moment–curvature diagram for a reinforced concrete pile. The stiffness is the moment of inertia (I) times the Young's modulus (E) of the concrete. Initially the concrete is uncracked. From point A on some sections start to crack and the stiffness decreases significantly, even with a moderate increase in loading, until point B is reached. At point B all the cracks have developed and the load can be increased up to point C where the steel starts to yield. The stiffness from point B to point C is the stiffness of a cracked concrete section.

The stiffness of the concrete pile for a given load level is illustrated more clearly in **Figure 6.4**, which shows the first derivative of the process. It can be seen that for a very small load increase, the deformations of the concrete will increase tremendously due to the cracking. Thus, even with almost no change in the soil, the head deformations of the pile may increase significantly and rapidly because of cracking.

The dashed line in Figure 6.4 shows the limit of the service load, that is the design load without a safety factor. It can be seen in Figure 6.4 that this load for sparsely reinforced sections is just slightly greater than the crack load. The concrete sections needed for geotechnical applications are normally large and the reinforcement ratio is usually low. Thus,

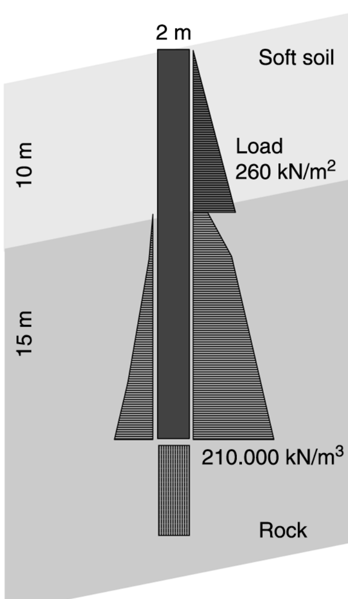

Figure 6.1 Slope investigated

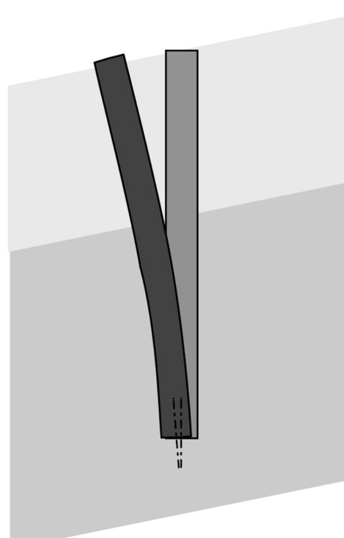

Figure 6.2 Generic pile deformation

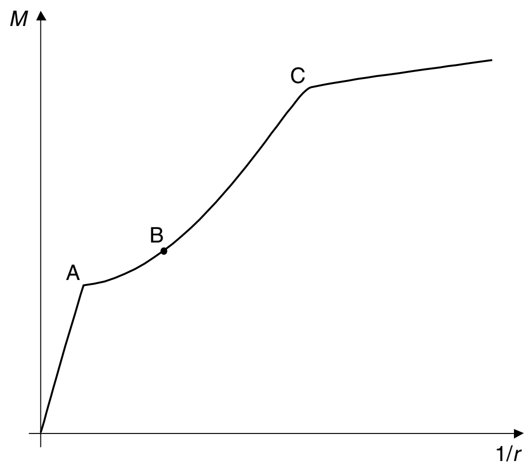

Figure 6.3 Generic moment–curvature diagram

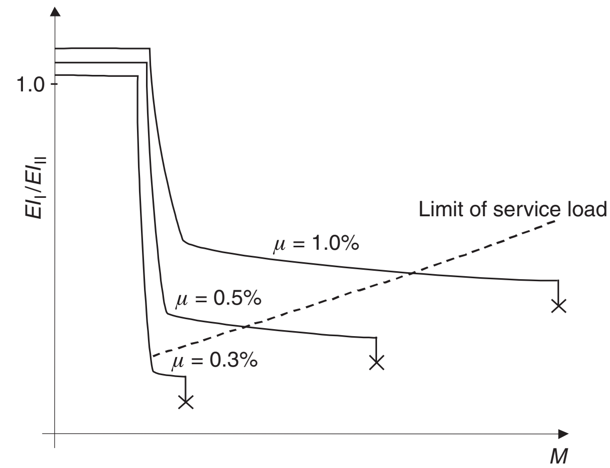

Figure 6.4 Stiffness–load level diagram

the pile may establish a cracked as well as an uncracked performance. Creep and shrinkage will increase the deformations of the concrete pile as well, but this will not be detailed here, since this process may be insignificant because of the moist environment the pile is exposed to.

6.1.5 Spaced pile wall

It is difficult to predict the correct stiffness of the concrete piles, as explained above. Thus a sensitivity analysis was performed to see how the deformation change depends on the pile stiffness. To simulate an uncracked pile, the pile stiffness was assumed to be E, I (E=30.000 MN/m^2, $I = \pi d^4/64$). The stiffness of the cracked pile was assumed to be one third of the uncracked pile stiffness. This should account for the average cracking, tension stiffening, creep and shrinkage. Compared with the deformation of the uncracked pile (**Figure 6.5**), the deformation of the cracked pile increases significantly (**Figure 6.6**). A head deformation of 45 cm may be unacceptable in most cases, however, this example illustrates the influence of the pile stiffness. In the project (Hartl, 1997) a anchorage of the pile heads was investigated next. The head deformation was much lower, but the concrete stiffness still had an effect on the system forces.

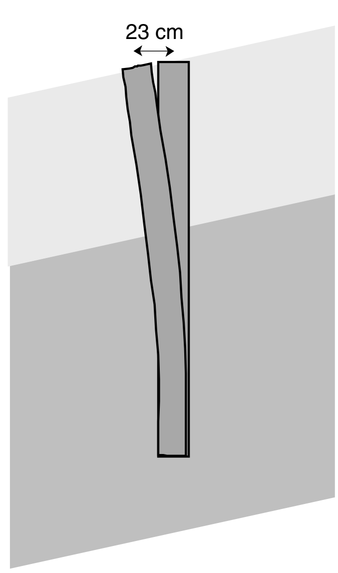

Figure 6.5 Head deformation of an uncracked pile

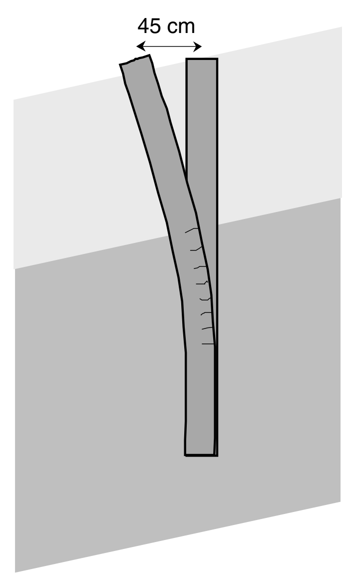

Figure 6.6 Head deformation of a cracked pile

6.1.6 Elliptical shaft foundation

Cracks in a shaft foundation are less likely to develop since the tensile stress in the concrete is less than the tensile stress in the piles. However, the same sensitivity analysis as for the drilled piles was performed. The stiffness for the cracked shaft was again assumed to decrease by a factor of three. Owing to the greater stiffness of the elliptical shaft compared with that of the drilled piles, the rigid body motion of the shaft in the soil is the most important component of the deformation. The internal deformation due to internal forces in the shaft is much lower. Thus the computed deformations increase by just 2.5 cm from 11 cm for the uncracked shaft (**Figure 6.7**) to 13.5 cm for the cracked shaft (**Figure 6.8**).

6.1.7 Conclusion and outlook

The computed deformation of the pile head consists of two components. First, the rigid body motion in the soil; the magnitude of this deformation is dependent on the size of the concrete pile and the stiffness of the embedding soil. Secondly, the internal deformation of the concrete pile; the magnitude of this deformation is dependent on the stiffness of the reinforced concrete pile. If both components are of equal order of magnitude, it is important to have a good constitutive model for both the soil and the reinforced concrete. This inspired the author to develop a computer program to consider the non-linear effects of the soil as well those of concrete within one coupled analysis. Both materials are modelled within a continuum mechanics approach. This was carried out within the PhD thesis of the author (Hartl, 2002), where an existing finite element code (Beer, 1999) has been extended for a concrete module. Some publications are available (Hartl and Beer, 2000; Hartl and Elgamel, 2000; Hartl *et al.*, 2000; Hartl, 2001) and the program was also tested by some students for several interaction problems (Lerchner, 2000; Brunner, 2001; Lerchner and Hartl, 2001; Pernthaner, 2001), with promising results.

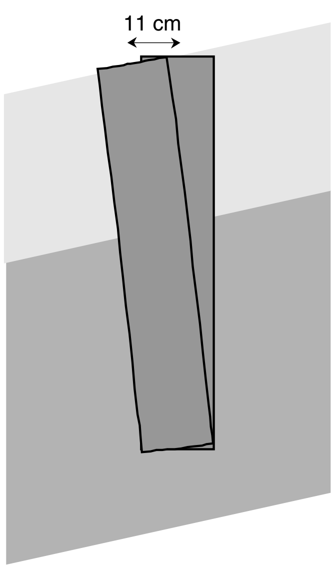

Figure 6.7 Head deformation of an uncracked shaft

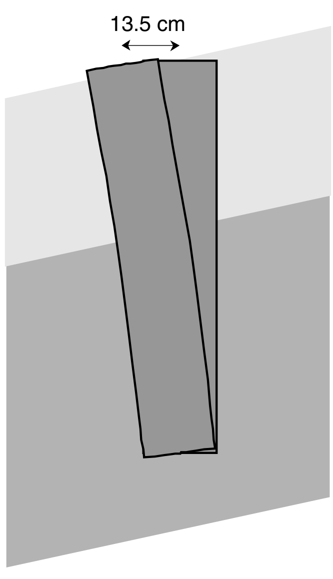

Figure 6.8 Head deformation of a cracked shaft