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SEMI-EMPIRICAL DESIGN OF HIGHWAYS ALONG UNSTABLE SLOPES

According to the engineering philosophy of "semi-empirical design" and "observational method", several highways (and railways) in the Alpine Region were constructed during the past 25 years along unstable slopes which years before had been considered unsuitable for such alignments. In many sections of Austrian highways about 75% of the alignment is running on slope bridges and aqueducts. Nevertheless, the visible part of these highways represents frequently only about 20% of the construction costs, whereas the other 80% are invisible, i.e. foundations, retaining structures, and prestressed anchors (up to a single length of 120 m).

In mountainous regions, the ground parameters frequently exhibit wide scattering (even within a small area) to such an extent that geotechnical design procedures seem to provide only border values and serve for reference only. The mean design value can only be a "most probable" value and has to be validated by the observational method. Due to the steeply inclined slopes, there is also the problem of seepage flow, and, moreover, seismic aspects have to be considered. The results of evaluating slope stability or the calculative lateral pressure on retaining structures are less influenced by the method of calculation than by the assumption of relevant soil/rock properties, seepage flow conditions, and seismic parameters. This is the reason why, generally, sophisticated design methods are by far less informative than parametric studies involving geological variability, groundwater conditions, and specific construction measures.

The optimal solution for slide stabilisation and retaining structures can frequently be achieved only step by step in connection with taking in situ measurements. It would be economically unjustifiable to construct most expensive protective structures, by throughout assuming and superposing the most unfavourable parameters.

"Calculated risks" are to be accepted in the design of roads and expressways through valleys in mountainous areas where slopes with a slide potential extend over distances of several kilometres. Risk assessment has to distinguish between the possibility of local slides and the stability against general failure. In order to reduce construction costs as well as to save time, the application of supplementary construction methods, typically anchors (prestressed), should be considered. Such measures are - even in connection with local remedial works - less costly than an "absolutely safe", fully engineered design which seeks to avoid the possibility of additional measures taken at a later time. Finally, one should bear in mind that an "absolute safety" cannot be provided under such extreme topographical and geotechnical conditions.

In such cases, flexible retaining structures have proved effective. They are adaptable step by step, both technologically as well as economically, to the locally prevailing slope pressures, slope movements, and ground conditions. This practical approach is based on continuous measurements and observations of the retaining structure, the surface and the subsoil/rock surface during the entire construction period (e.g. by geodetic survey, extensometers, and inclinometers, monitoring anchors, earth/rock pressure cells). After completion of construction, subsequent random monitoring is recommended. Calculations and theoretical considerations are only the basis for the first design and for interpreting the obtained measurement results. This "semi-empirical" design method has proved suitable under most difficult conditions for more than 25 years.

In case of statically very sensitive buildings (e.g. slope bridges with continuos girder superstructures) the foundation requires a high resisting movement (e.g. large diameter caissons, sometimes with multiple anchorage). That means that rather rigid (and deep) footings have to be designed. Nevertheless, even such buildings should be protected – in addition – at the hillside by a flexible retaining structure which simultaneously acts as a first barrier (="primary" retaining system) against excessive slope pressures. As the latter may change with time, a long-term monitoring of sensitive structures in slide-prone, deeply inclined slopes is unavoidable.

In many cases of ground engineering under difficult conditions this philosophy provides the only technical solution - not to mention the cost savings. A "fully engineered" design, i.e. a design which requires no further modification following detailed design is hardly possible. The potential to make modifications during construction and to strengthen the structure at any time, also after construction, is a fundamental requirement of the observational method or the semi-empirical design method respectively. It involves the concepts of the most probable and most unfavourable conditions, hence a creative process and not over-complication, but "high-quality simplicity": High-quality simplicity does not forget the reasoning behind "simple" practices, because over-simplification, sometimes through so-called high-tech mechanistic calculations, can cloud one's engineering judgement.

Risk assessment in connection with creeping ground and progressive failure of slopes is especially critical if statically sensitive bridges have to be constructed there. Monitoring should begin as early as possible before starting construction. Numerous measurements over a period of 25 years have revealed that a creeping pressure acts on retaining structures and foundations in such unstable zones which exceeds widely the earth pressure at rest but hardly approaches the passive boundary value. Figure 1 shows how many retaining measures are required to take over these lateral forces for a bridge abutment on top of a valley in an unstable slope. The structure had to be tied back in the longitudinal and transversal direction with prestressed grout anchors up to 55 m length.
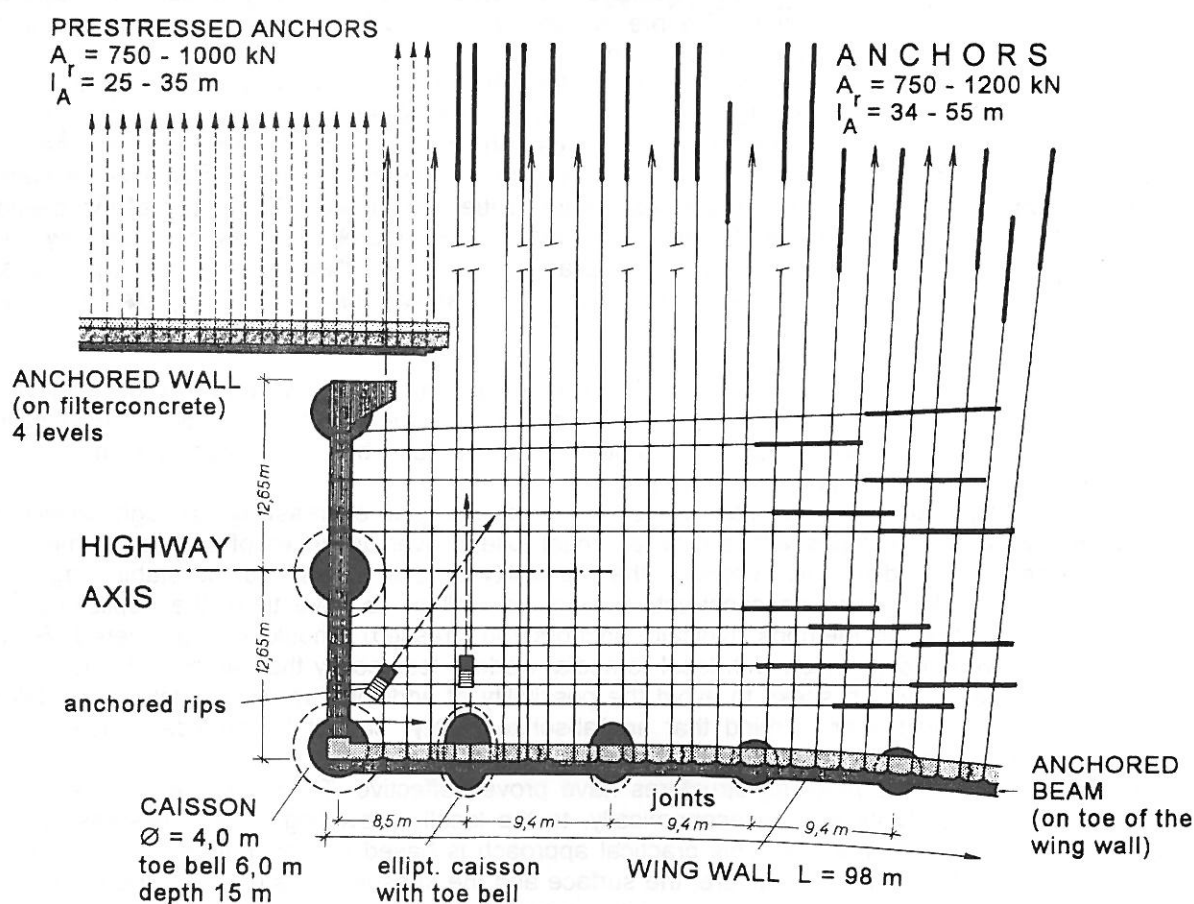

Figure 1. Ground plan of a highway bridge abutment in a steeply inclined unstable slope. Foundation on caissons and geotechnical anchoring in both directions. Retaining walls also intensively tied back with prestressed anchors. Only anchors of one of a total of four levels are indicated. $A_r = T_w$ = working load.

Figure 2 shows the cross section of a slide-prone slope where a highway had to be constructed. In order to minimise the slope cut, a "semi-bridge" was designed. Its foundation is by far deeper than the visible part above ground surface. Moreover, silty slope deposits of mica schist required an intensive anchorage of the whole structure.
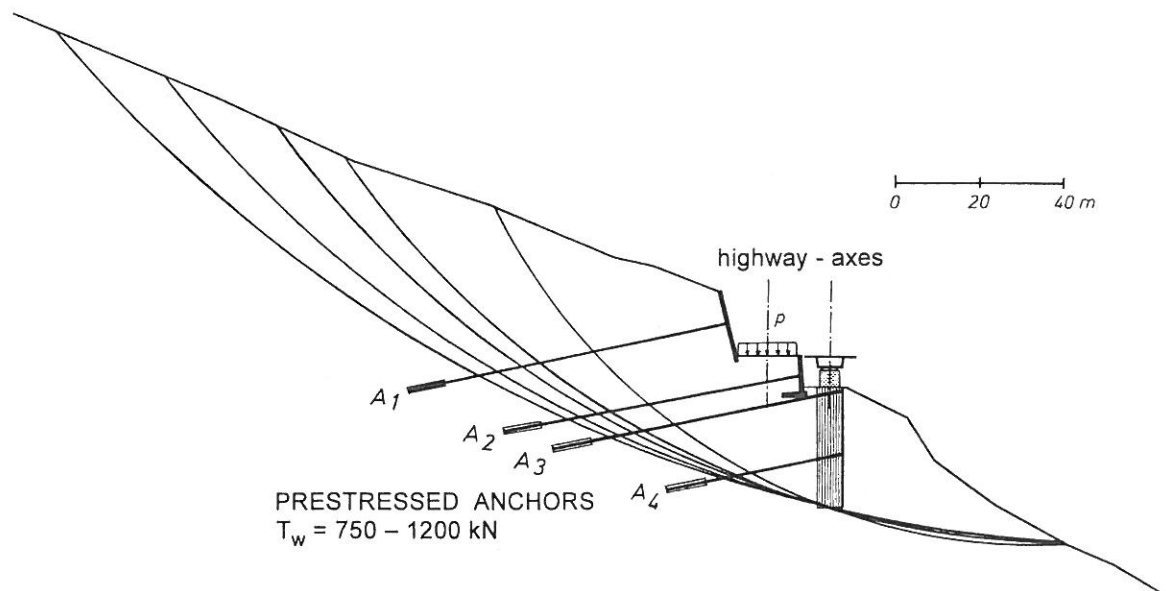
Figure 2. Cross section of a "semi-bridge" on deep caissons in a slide-prone slope. Bridge, cantilever wall, and element wall tied back with prestressed anchors. Example for assessing the required anchor lengths from various slide surfaces, running through the caisson's base.
A_1 = resultant of anchor forces of the anchored element wall
A_2 = resultant of anchor forces of the tied back cantilever wall
A_3 = resultant of anchor forces on top of the caisson (remaining accessible).
A_4 = resultant of anchor forces within the caisson (only remote reading possible)

The calculation of the 17 to 22 m high anchored element wall in Figure 2 is a typical example illustrating the extreme influence of the ground's shear properties on the required anchor forces (Figure 3): Even in the only 17 m high wall section the necessary anchor forces for achieving a safety factor of F = 1 varied by ΔA = 1000 kN per m run if the friction angle varied by only $\Delta\Phi$ = 1°. But actually, the internal friction exhibited a scatter of $\Delta\Phi$ = 15°, and, moreover, it could drop to the residual shear value Φ_r clearly lower than Φ. The cohesion also exhibited a strong influence on the results of calculation, hence leading to a great difference between "Most Probable"(MP) and "Most Unfavourable" (MU) conditions. This example is therefore very characteristic of the advantage of the observational method or semi-empirical design respectively over the fully engineered design method. The half bridge exhibits multi-anchored caissons with remote monitoring of the anchor forces. In the top zone of the caissons and in the retaining walls, tubes have been installed to make - in case of danger - subsequent strengthening possible, rapidly and at all times.
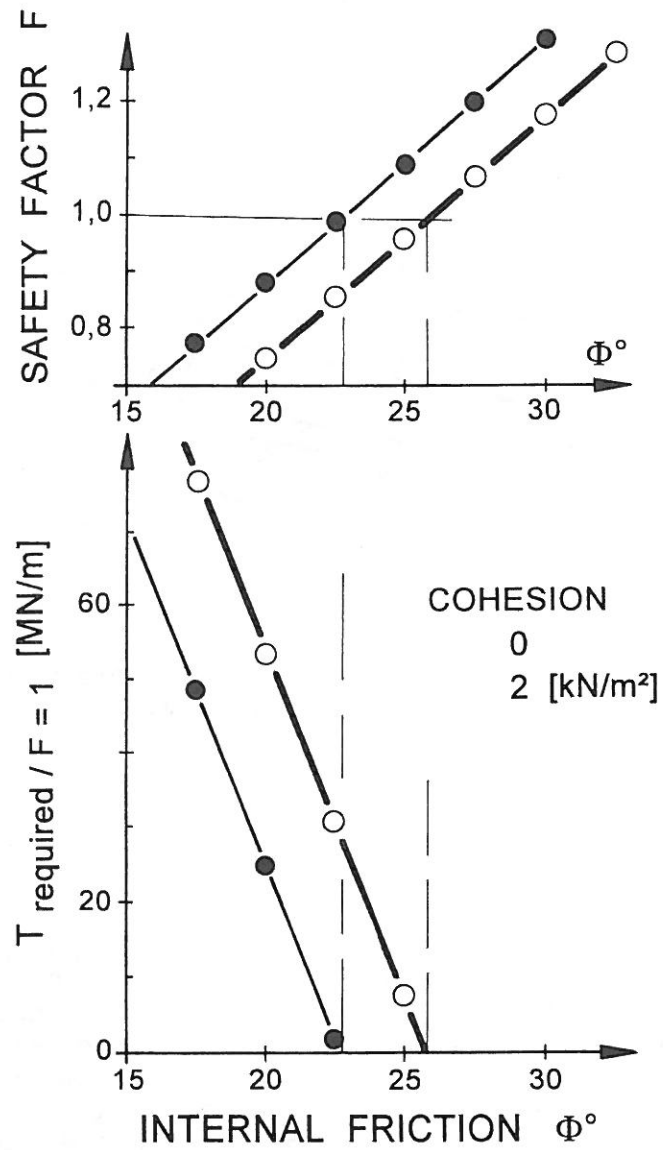
Figure 3. Influence of shear parameters on the safety factor against slope failure, F, and on the required anchor force T(A) per meter run of the structure to achieve F = 1 for the anchored element wall above the "semi-bridge" in Figure 2.