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Optimization of temporary anchor systems for high voltage electricity masts

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ABSTRACT: For the construction of high voltage electricity lines the masts need temporary anchor systems to transfer tension loads into the subsoil. In engineering practice, totally different systems are used: deadman constructions, counterweights and the so called Spinnanker. Deadman constructions are steel beams or steel pipes, which are buried in the subsoil. The resistance occurs due to the passive earth pressure. For counterweights, large concrete blocks are used to activate the sliding resistance. The Spinnanker consists of an anchor plate and threaded steel bars, which are screwed into the subsoil. The resistance is a combination of skin friction of the steel bars and of the passive earth pressure. Deadman constructions and counterweights are two well-known systems, but cause a lot of tillage and use of material and thus have a massive impact on the environment. The Spinnanker is a new construction system, which is minimally invasive. Based on a real construction project in Germany these three different temporary anchor points are analyzed regarding the construction method and the design and safety concept. The paper introduces the three different systems and explains the results of the analysis. Finally, recommendations for the field of application, the construction and the secure and economic design are given.

KEYWORDS: temporary anchor systems, resource minimization, deadman construction, counterweight, Spinnanker.

1 INTRODUCTION

Temporary anchor systems are essential during construction to transfer tensile forces safely into the ground. To ensure efficiency and sustainability, these systems should have minimal environmental impact, helping to conserve resources, reduce CO_2-emissions, and lower both time and financial costs. The design process must carefully consider all geotechnical factors, including soil composition, groundwater conditions, and applicable safety standards. These considerations are critical for assessing both the structural stability and functionality of the system. Several types of temporary anchors are commonly employed for this purpose:

- deadman structures
- counterweights
- Spinnanker

In engineering practice, various design methods are used for deadman anchors and counterweight systems. Typically, no in-situ load testing is performed for these temporary anchors, resulting in a level of safety that often remains uncertain. This paper outlines the appropriate design approach based on the guidelines provided in EN 1997-1.

2 DEADMAN STRUCTURES

2.1 *Basics*

Deadman anchors typically consist of timber beams, steel beams, or steel pipes embedded in the ground. While EN 1997-1 provides partial guidance, it does not comprehensively address the design of these systems. In current engineering practice, a commonly used approach references parts of EN 1997-1 but is also based on assumptions that may overestimate soil resistance. To address this limitation, the authors have developed a more robust design methodology that systematically considers all relevant geotechnical failure mechanisms based on the principles of EN 1997-1:

- horizontal stability
- vertical stability
- inclined sliding stability

Figure 1 illustrates the basic system of a deadman construction, including its geometric parameters and the characteristic tensile force F_k (kN), which is derived from both permanent and variable loads. For a conservative design approach, a partial safety factor of $\gamma_Q = 1.3$ according to DIN 1054 is applied to account for the effects of loading.

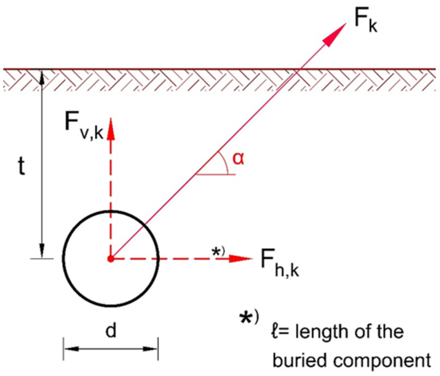

Figure 1. Principal system of a deadman structure (sectional view).

2.2 *Analysis of the horizontal stability*

For the analysis of the horizontal stability according to the principles of EN 1997-1, the horizontal impact $E_{h,d}$ (kN) is compared to the horizontal earth resistance $R_{h,d}$ (kN). The horizontal impact consists of the horizontal component $F_{h,k}$ (kN) of the tension force F_k (kN) and the active earth pressure $e_{ah,k}$ (kN/m²). All forces are shown in Figure 2.

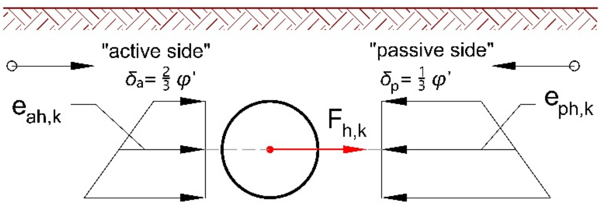

Figure 2. Horizontal components (sectional view).

The total impact $E_{h,d}$ is defined in Equation (1) , incorporating a partial safety factor of $\gamma_G = 1.2$ for the earth pressure.

$$E_{h,d} = F_{h,k} \cdot \gamma_Q + e_{ah,k} \cdot d \cdot l \cdot \gamma_G \qquad (1)$$

In the analysis of horizontal stability, the resistance $R_{h,d}$ is defined as the passive spatial earth pressure $e_{ph,k}$ (kN/m²). This pressure depends on the length l (m) and diameter d (m) of the buried component, as well as the soil's friction angle φ′ (°). In the case of a deadman anchor the coefficient $\mu^{(res)}$ (-) used for calculating the spatial earth pressure is determined by Equation (2) for the soil's dead load, and by Equation (3) for cohesion according to DIN 4085, which defines the determination of earth pressure. The design value of the resistance $R_{h,d}$ is given in Equation (4), with a partial safety factor of $\gamma_{R,e} = 1.3$.

$$\mu_{pg}^{(res)} = 1 + 0{,}6 \cdot \frac{d}{l} \cdot \tan \varphi' \tag{2}$$

$$\mu_{pc}^{(res)} = 1 + 0{,}3 \cdot \frac{d}{l} \cdot (1 + 1{,}5 \cdot \tan \varphi') \tag{3}$$

$$R_{h,d} = \frac{R_{h,k}}{\gamma_{R,e}} = \frac{e_{pgh,k} \cdot d \cdot \mu_{pg}^{(res)} + e_{pch,k} \cdot d \cdot \mu_{pc}^{(res)}}{\gamma_{R,e}} \cdot l \tag{4}$$

The final verification in the horizontal stability analysis according to EN 1997-1 is presented in Equation (5):

$$E_{h,d} \leq R_{h,\mathrm{d}} \tag{5}$$

2.3 *Analysis of the vertical stability*

In the analysis of vertical stability based on the principles of EN 1997-1, the vertical impact $E_{v,d}$ (kN) is compared to the vertical earth resistance $R_{v,d}$ (kN). The vertical impact comprises the vertical component $F_{v,k}$ (kN) of the tension force F_k. The vertical earth resistance $R_{v,d}$ consists of the soil's dead load G_k (kN), the friction force $R_{s,k}$ (kN) acting within the shear zone above the buried component as well as the vertical component of the passive earth pressure $E_{pv,k}$ (kN). All relevant forces are illustrated in Figure 3.

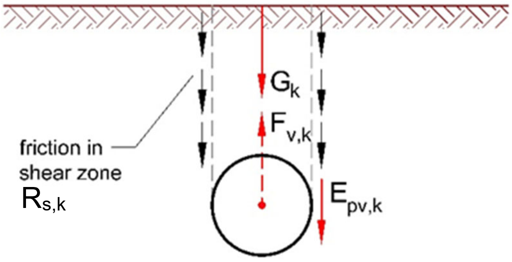

Figure 3. Vertical components (sectional view).

The calculation of the total impact $E_{v,d}$ is shown in Equation (6).

$$E_{v,d} = F_{v,k} \cdot \gamma_Q \tag{6}$$

The dead load of the soil G_k is determined by the geometry above the buried component, the weight of the buried component $G_{bc,k}$ (kN), and the weight of the soil γ (kN/m³), as shown in Equation (7). In the presence of groundwater, the weight of the soil is replaced by the weight γ'.

$$G_k = (\gamma \cdot d \cdot (t - d) \cdot l) + G_{bc,k} \tag{7}$$

The friction force $R_{s,k}$ arises from the horizontal earth pressure at rest E_0 (kN) acting within the shear zone located above the buried component. The area of this shear zone corresponds to the circumference of the ground view of the buried component. The earth pressure E_0 and the resulting friction force $R_{s,k}$ are calculated using Equations (8) and (9) according to DIN 4085.

$$E_0 = \gamma \cdot (1 - \sin \varphi') \cdot \left(t - \frac{d}{2}\right) \cdot \frac{t - d/2}{2} \cdot (2 \cdot l + 2 \cdot d) \tag{8}$$

$$R_{s,k} = E_0 \cdot \tan \varphi' \tag{9}$$

The calculation of the vertical component of the passive spatial earth pressure depending on the resistance $R_{h,k}$ (kN) (see Equation (4)) and the soil's friction angle φ' (°), is described in detail in the following Equation.

$$E_{pv,k} = R_{h,k} \cdot \tan\left(\frac{1}{3}\varphi'\right) \tag{10}$$

The total resistance $R_{v,d}$ can be calculated as follows:

$$R_{v,d} = \frac{G_k + R_{s,k} + E_{pv,k}}{\gamma_{R,e}} \tag{11}$$

The final proof in the analysis of the vertical stability according to the principles of EN 1997-1 is as follows:

$$E_{v,d} \leq R_{v,\mathrm{d}} \tag{12}$$

2.4 *Analysis of the inclined sliding stability*

To analyze inclined sliding stability, the mobilized soil body is idealized as a wedge with its base oriented in the direction of the tension force F_k (kN). The impact E_d (kN) acting on this wedge is then compared with the available sliding resistance R_d (kN). The impact includes the tension force F_k and the component of the active earth pressure acting parallel to the sliding plane, $E_{a,\parallel,k}$ (kN/m) and the associated partial safety factors γ_Q (-) and γ_G (-) according to DIN 1054. The impact E_d, based on EN 1997-1, is defined by Equations (13) and (14).

$$E_d = F_k \cdot \gamma_Q + E_{a,\parallel,k} \cdot \gamma_G \cdot l \tag{13}$$

$$E_{a,\parallel,k} = E_{ah,k} \cdot \cos \alpha \tag{14}$$

The sliding resistance R_d is composed of several contributing forces:

- The friction force $R_{s,G,k}$ (kN) in the sliding surface, which results from the soil's dead load $G_{\perp,k}$ (kN)
- The downslope component of the soil's dead load $G_{\parallel,k}$ (kN)
- The friction force $R_{s,Ea,k}$ (kN), in the sliding surface, which results from the inclined component of the active earth pressure $E_{a,\perp,k}$ (kN/m)
- The friction force $R_{s,c,k}$ (kN) in the sliding surface due to soil cohesion
- The friction force $R_{s,E0,k}$ (kN) in the area A (m²), which results from the earth pressure at rest E_0 (kN)

All forces and the geometry of the sliding wedge are illustrated in the following figures.

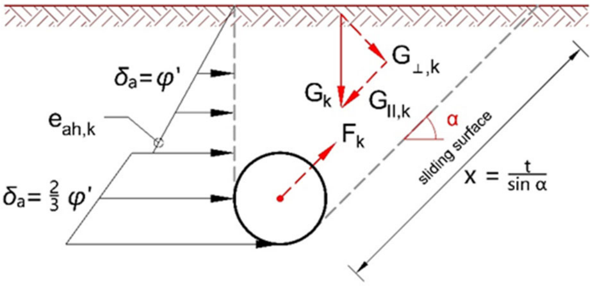

Figure 4. Sliding block (sectional view).

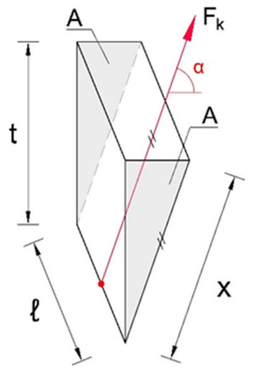

Figure 5. Sliding block (3-dimensional view).

Equations (15) to (20) define the individual components of the total resistance R_d. The coherences of the following equations are derived from the geometry and the known geotechnical principles.

$$R_{s,g,k} = G_{\perp,k} \cdot \tan\varphi' \tag{15}$$

$$G_{\perp,k} = G_k \cdot \cos\alpha \tag{16}$$

$$R_{s,Ea,k} = E_{a,\perp,h} \cdot \tan\varphi' \cdot l \tag{17}$$

$$E_{a,\perp,k} = E_{ah,k} \cdot \sin\alpha \tag{18}$$

$$R_{s,c,k} = c'_k \cdot x \cdot l \tag{19}$$

$$R_{s,E0,k} = 2 \cdot A \cdot \gamma \cdot (1 - \sin\varphi') \cdot \frac{t - {}^{d}/_{2}}{2} \cdot \tan\varphi' \tag{20}$$

$$G_{\parallel,k} = G_k \cdot \sin\alpha \tag{21}$$

The total resistance R_d is as follows:

$$R_d = \frac{R_{s,G,k} + R_{s,Ea,k} + R_{s,c,k} + R_{s,E0,k} + G_{\parallel,k}}{\gamma_{R,h}} \tag{22}$$

The final proof in the analysis of the inclined sliding stability according to the principles of EN 1997-1 is as follows:

$$E_d \leq R_d \tag{23}$$

2.5 *Safety and quality assurance*

At this point in time, the real load-displacement behavior of deadman structures has not been fully investigated, particularly under high loads in both small-scale and large-scale soil tests. According to EN 1997-1, deadman structures must be treated as anchor systems. As a result, in-situ load-displacement testing is required on each construction site unless comparable data is already available. The required test loads must comply with the regulations applicable to prestressed anchor systems.

3 COUNTERWEIGHTS

3.1 *Basics*

Counterweights are typically composed of large concrete blocks mounted on a steel frame. To enhance the frictional resistance between the counterweights and the subsoil, a layer of gravel is commonly used as bedding material. When designing such systems, the guidelines outlined in EN 1997-1 for individual foundation elements must be adhered to. The primary contributors to the system's stability are the self-weight of the counterweights and the frictional interaction with the subsoil. Based on these principles, the following design methodology is proposed, which accounts for all relevant geotechnical failure mechanisms:

- uplifting
- sliding stability
- limitation of the eccentricity
- bearing resistance

Figure 6 illustrates the conceptual arrangement of a counterweight system, including geometric parameters and the characteristic tensile force F_k (kN), which arises from both permanent and variable loads. For a conservative design, a partial safety factor of $\gamma_Q = 1.3$ according to DIN 1054 is applied.

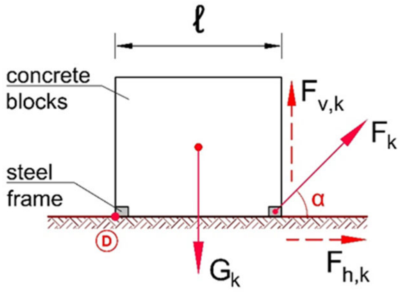

Figure 6. Principle system of a counterweight (sectional view).

3.2 *Uplift*

To evaluate the risk of uplift according to EN 1997-1, the vertical component $F_{v,k}$ (kN) of the tension force F_k is assessed in relation to the counterweight's characteristic dead load G_k (kN). For design purposes, the partial safety factors $\gamma_{G,stb} = 0.95$ and $\gamma_{Q,dst} = 1.30$ according to DIN 1054 are applied in accordance with Equations (24) and (25).

$$E_{v,d} = F_{v,k} \cdot \gamma_{Q,dst} \tag{24}$$

$$R_{v,d} = G_k \cdot \gamma_{G,stb} \tag{25}$$

According to EN 1997-1 is the final proof in the analysis of the uplifting as follows:

$$E_{v,d} \leq R_{v,d} \tag{26}$$

3.3 *Sliding stability*

To analyze the sliding stability, the horizontal component $F_{h,k}$ (kN) of the tension force F_k is compared to the available friction resistance $R_{h,k}$ (kN) beneath the counterweight. The resulting horizontal load is determined as follows:

$$E_{h,d} = F_{h,k} \cdot \gamma_Q \tag{27}$$

According to EN 1997-1, the friction resistance is influenced by the angle of friction δ_k in the subsoil below the surface:

$$R_{h,d} = \frac{(G_k - F_{v,k}) \cdot tan\,\delta_k}{\gamma_{R,h}} \tag{28}$$

Due to the plain surface between the precast concrete blocks and the steel frame, the angle of friction of the subsoil should be conservatively limited to $\delta_k = 2/3 \cdot \varphi'$. The partial safety factor of $\gamma_{R,h} = 1.1$ according to DIN 1054 is to be applied to the friction resistance. The final verification for sliding stability according to EN 1997-1 is conducted as follows:

$$E_{h,d} \leq R_{h,d} \tag{29}$$

3.4 *Limitation of the eccentricity*

To evaluate the limitation of eccentricity according to EN 1997-1, the moments at point D (as shown in Figure 6) are calculated. These moments result from the vertical component $F_{v,k}$ of the tension force F_k, as well as from the counterweight's dead load G_k. The resulting moment due to the applied loads and the resisting moment are given as follows:

$$M_{E,d} = F_{v,k} \cdot l \cdot \gamma_{Q,dst} \tag{30}$$

$$M_{R,d} = G_k \cdot \frac{l}{2} \cdot \gamma_{G,stb} \tag{31}$$

According to DIN 1054, the applied partial safety factors are $\gamma_{Q,dst} = 1.05$ for the design tension force and $\gamma_{G,stb} = 0.90$ for the stabilizing dead load. The final verification is presented in equation (32). Additionally, to ensure proper load distribution, EN 1997-1 requires that the eccentricity e under characteristic loading conditions not exceed l/3, as specified in Equation (33).

$$M_{E,d} \leq M_{R,d} \tag{32}$$

$$\frac{F_{v,k} \cdot {}^{l}/_{2}}{G_k - F_{v,k}} \leq \frac{l}{3} \tag{33}$$

3.5 *Bearing resistance*

Bearing resistance failure occurs when the applied load induces excessive stress in the subsoil. According to EN 1997-1 two critical loading scenarios must be evaluated:

- maximum loading resulting from the counterweight itself
- maximum eccentricity generated by the vertical component of the tension force

A key aspect of the analysis is the eccentricity e, which reduces the effective base length from l to l', where l' = l – (2 · e). The impact V_k (kN) is calculated as the counterweight's dead load G_k reduced by the vertical component $F_{v,k}$ of the tension force F_k. The impact on the design level is described by equation (34):

$$V_d = (G_k - F_{v,k}) \cdot \gamma_Q \tag{34}$$

The bearing resistance $R_{v,k}$ depends according to EN 1997-1 on several factors, including the effective base area of the counterweight, the angle of friction φ' (°), the cohesion c' (kN/m²) and the inclination of the applied load. The counterweight does not have any embedment depth. The design bearing resistance is determined as follows:

$$R_{v,d} = \frac{R_{v,k}}{\gamma_{R,v}} \tag{35}$$

According to EN 1997-1, the final proof in the analysis of the bearing resistance is as follows:

$$V_d \leq R_{v,d} \tag{36}$$

4 SPINNANKER

4.1 *Basics*

The Spinnanker represents a modern foundation and anchoring solution, utilizing threaded steel rods that are directly screwed into the ground. This system is suitable for installation in both cohesive and non-cohesive soils, using a hand-held turning tool. Standard versions include 6 to 18 steel bars, which are inserted through a circular anchor plate into the subsoil. Figure 7 displays an example of a Spinnanker model XII / 2.0 / 15. The bars are available in diameters of 15, 18, 20, and 26 mm, with lengths ranging from 2.0 to 8.0 meters, and can be installed at various inclination angles depending on the design requirements. The diameter of the plate, the number of bars, and their length are selected based on soil properties and the applied loads. A detailed overview of potential applications can be found in Katzenbach et al. (2019a). As illustrated in Figure 8, the system can be used, for example, to anchor infrastructure for a new 380 kV high-voltage transmission line.

Figure 7. Spinnanker XII / 2.0 / 15 (12 threaded bars with a length of 2.0 m and a nominal diameter of 15 mm).

Figure 8. Anchoring with Spinnankers for a new 380 kV high-voltage line in Germany.

4.2 *Load-deformation behaviour*

The load-deformation characteristics of the Spinnanker system can be effectively evaluated through vertical pull-out tests. A representative load–displacement curve from such a test is shown in Figure 9. In this example, the system reached a maximum load of 180kN with a corresponding displacement of just 2.5 mm.

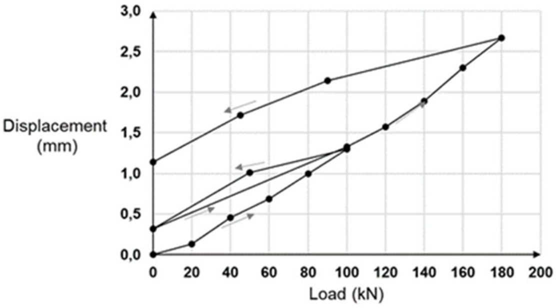

Figure 9. Vertical pull-out test on a Spinnanker XII / 3.0 / 15 in fine and medium sand with medium density.

4.3 *Design and safety factor*

The design process begins with a preliminary design, drawing on data from a large number of previous load tests. This is followed by a final design stage, which is based on in-situ suitability load tests. These tests provide the characteristic bearing capacity value $R_{t,k}(\vartheta, n_{Sp})$ in kN, taking into account the load inclination angle (ϑ) and the use of a group of Spinnankers (quantity n_{Sp}). For the ultimate limit state, the load bearing capacity is determined by applying appropriate partial safety factors in accordance with EN 1997.

$$R_{d,\vartheta} = \frac{R_{t,k}(\vartheta, n_{Sp})}{\gamma_{s,t}} = \frac{R_{t,k}}{\gamma_{s,t}} \cdot k_\vartheta \cdot k_n \qquad (37)$$

Equation (36) incorporates two correction factors: k_ϑ, which accounts for the inclination of the load, and k_n, which adjusts for the number of Spinnankers used in a group. Based on the results of in-situ load testing, a partial safety factor for resistance of $\gamma_{s,t} = 1.15$ is applied. The design resistance $R_{d,\vartheta}$ (kN) must exceed the design load $E_{d,\vartheta}$ (kN), which represents the resultant force acting in the direction defined by $\vartheta = \alpha$ (°).

$$E_{d,\vartheta} \leq R_{d,\vartheta} \qquad (38)$$

To ensure a conservative design for the applied load $E_{d,\vartheta}$, a partial load factor of $\gamma_Q = 1.3$ is applied. A comprehensive explanation of the design methodology and safety concept can be found in Katzenbach et al. (2019b) and Leppla et al. (2022).

5 COMPARISON OF ANCHOR POINTS

Using an example from engineering practice, three different types of temporary anchor systems were designed under the same boundary conditions:

- tension force: $F_k = 120$ kN, inclination: $\alpha = 60°$
- medium dense sand/gravel:
  $\gamma = 19$ kN/m³, $\varphi' = 32.5°$, no groundwater

The resulting designs for the three anchor systems, in accordance with the calculation approach described above and EN 1997-1, are summarized below:

- deadman structure:
  steel pipe, diameter d = 406 mm, length l = 4 m,
  depth t = 3 m, thickness of steel t = 16 mm, ca. 628 kg
- counterweight:
  precast concrete blocks, C20/25, total volume 13.8 m³
  and 31.8 tons, ground area of 2.4 m / 2.4 m,
- Spinnanker:
  1 x XII / 4.0 / 15 with only 100 kg of steel

Regarding the impact of construction processes on the environment, the reduction of CO_2 has an important role. The production of construction materials, e.g. steel and concrete, consume large amounts of energy leading to a large emission of CO_2. To compare the emissions of CO_2 of the different temporary anchor systems, the Global Warming Potential (GWP) is used. The GWP is a metric in which the greenhouse gas potential of other substances can be measured relative to CO_2.

In ÖKOBAUDAT, the German Federal Ministry for Housing, Urban Development and Building (BMWSB) provides information on GWP, which complies with EN 15804, for various materials. For example, the production of 1 kg hot-rolled steel section manufactured via the electric arc furnace route in Germany results in a GWP of 1.459 kg CO_2e (BMWSB). The production of 1 m³ of C20/25 concrete with a bulk density of 2,400 kg/m³ results in a GWP of 178 kg CO_2e (BMWSB), while the production of 1 kg reinforcing steel bars yields in a GWP of 0.474 kg CO_2e (BMWSB).

For the three anchor solutions, the GWPs are calculated as follows based on the previous characteristic values and considering only emissions for the manufacturing phase (Modules A1-A3, according to EN 15978 and EN 15804) for the main material:

- deadman structure:
  628 kg steel section ≈ 910 kg CO_2e
- counterweight:
  13.8 m³ of concrete ≈ 2,500 kg CO_2e
- Spinnanker:
  100 kg steel bars ≈ 50 kg CO_2e

All three anchor solutions can be re-used. It is easy to see, that the Spinnanker has the smallest GWP while the counterweight has the greatest GWP regarding the production of the construction material. For an overall evaluation the efforts for installation and transport have to be considered.

For the transport and the installation of a deadman structure the following efforts exist:

- site development including land improvement
- transport of a mobile excavator and of the steel pipe to the project area
- excavation of the installation pit and installation of the steel pipe
- fill and compaction of the installation pit
- excavation of the installation pit and deinstallation of the deadman structure
- fill and compaction of the installation pit again
- transport of a mobile excavator and of the steel pipe from the project area
- removal of site development including land improvement

For the transport and the installation of a counterweight the following efforts exist:

- site development including land improvement
- transport of a mobile crane and of the concrete blocks to the project area
- installation of the counterweight
- deinstallation of the counterweight
- transport of a mobile crane and of the concrete blocks from the project area
- removal of site development including land improvement

For the transport and the construction of a deadman structure and of a counterweight, massive efforts for site development including land improvement are necessary because heavy trucks and machines are used.

For transport and installation of a Spinnanker only one small pickup truck is necessary. All components of a Spinnanker can be carried by men to the project area. For the installation only handheld machines are used. There is no need for a complex site development including land improvement.

Under consideration of all aspects regarding CO_2-emission for the installation of temporary anchor points for high voltage electricity masts the Spinnanker has the smallest impact on the environment at all.

6 CONCLUSIONS

As demonstrated, the design approaches for the three temporary anchoring systems differ significantly. One critical distinction lies in the safety level: for deadman anchors and counterweights, in-situ load tests are typically not performed in standard engineering practice. This introduces a degree of uncertainty in the design process and results in a lower level of safety compared to systems that are directly tested on-site.

Moreover, the construction effort and resource consumption associated with each system must be carefully evaluated. Optimizing both the design and construction phases contributes directly to a reduction in CO_2 emissions.

When planning and designing temporary anchor systems, the following key aspects and requirements should be taken into account:

- A geotechnical investigation, including soil and groundwater conditions, must be conducted by qualified professionals.
- The installation of deadman anchors and counterweights has a significant environmental impact due to the scale of excavation and material usage.
- The Spinnanker system is designed based on in-situ load testing, ensuring a clearly defined safety level and allowing for cost-effective, optimized design.
- In comparison to conventional methods, the Spinnanker system results in lower CO_2 emissions.
- According to EN 1997 standards, the bearing capacity of all anchoring systems must be verified through in-situ load testing. Therefore, load tests should also be performed for deadman and counterweight solutions to meet regulatory requirements. This is necessary to check the estimated boundary conditions and the applied theoretical models for the analysis of the stability.

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