Ground improvement methods with special emphasis on column-type techniques

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ABSTRACT: In this paper the main emphasis is put on methods for the improvement of soft soils using column-type techniques. The following methods will be discussed: stone columns, sand compaction piles, grout injected stone columns with load transfer mats constructed with geosynthetic reinforcements, CSV-method, geotextile encased sand columns, FMI-method, lime and lime cement columns and friction piles in soft soils. The current state-of-the-art on these techniques, some research results and the experiences gained from two important projects are presented. The report is concluded with an evaluation matrix.

1 INTRODUTION

Ground improvement methods using column-type techniques are used on an increasing scale for the construction of road and railway embankments. The basic principle of these techniques is to relieve the load on the soft soils without altering the soil structure substantially. This is achieved by installing column- or pile-type structures in a grid pattern into a bearing layer, on top of which often a load transfer mat consisting of geotextile or geogrid reinforcements is constructed. The stress relieve of the soft soils results from a redistribution of the loads in the embankment through arching, which (if present) is stabilized by the geotextil/geogrid reinforcement (membrane effect) additionally. As a result the compressibility of the improved or composite ground can be reduced and the bearing capacity and shear strength increased. The consolidation of the soft soils can also be accelerated and thus the settlements after construction may be minimized considerably, since most column-type structures act as a vertical drain.

Column-type soil improvement techniques are also be used for the foundation of tanks and warehouses.

2 STONE COLUMNS AND SAND COMPACTION PILES

2.1 *Description*

Stone columns and sand compaction piles (or composer piles) represent the most known column-type technique for improving soft soils. Various installation methods are used worldwide, for instance the vibro replacement method (fig. 1) and the vibro composer method. The effectiveness of the load redistribution to the columns mainly depends on the lateral support of the columns which can be provided by the surrounding soft soil. The lateral support is expressed by means of the undrained shear strength. According to German regulations, stone columns can be applied, if soft soils have an undrained shear strength of $c_u \geq 15$ - 25 kN/m^2 *(FGSV 1979)*. Occasionally stone columns are installed in very soft soils having an undrained shear strength $c_u < 10$ kN/m^2 (*Raju 1997)*. Generally, however, there is a risk in installing stone columns in sensitive or organic soils.

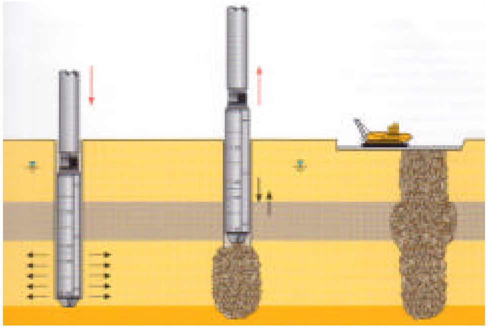


Figure 1. Vibro replacement method (after Keller Grundbau)

2.2 *Design principles*

An overview and comparison of existing design methods is given for instance by *Soyez (1987)* and *Bergado, Chai, Alfaro & Balasubramaniam (1994)*. Most design methods are based on the ‘unit cell concept’, i.e. a cylinder of composite ground enclosing the tributary soil and a column is considered. The effect of a soil improvement is usually expressed by an improvement factor β:

$$b = \frac{\text{Settlement of unimproved soil}}{\text{Settlement of improved soil}} \tag{1}$$

Several methods for calculating this factor and thus designing the column grid are described in literature. In Europe the analytical method of *Priebe (1995)* is often used. Using some simplifications and assumptions Priebe expresses the soil improvement factor β as:

$$b = 1 + a_C \cdot \left[\frac{0{,}5 + f(n, a_C)}{K_{a,C} \cdot f(n, a_C)} - 1 \right] \tag{2}$$

$$K_{a,C} = \tan^2 (45° - \frac{f_C}{2}) \text{ and } f(n, a_C) = \frac{1 - n^2}{1 - n - 2n^2} \cdot \frac{(1 - 2n) \cdot (1 - a_C)}{1 - 2n + a_C} \tag{3}$$

where a_C (area replacement ratio) = A_C/A_E, A_C = cross sectional area of column, A_E = cross sectional area of unit cell and ν = Poisson’s ratio of soil. Other methods are cited in *Goughnour & Bayuk (1979)*, which take into account the effect of the column installation through the coefficient of earth pressure, that depends on the magnitude of the deformation.

3 GROUTED STONE COLUMNS, PREMIXED AND CONCRETE COLUMNS WITH REINFORCED BEARING LAYERS

3.1 *Description*

In very soft soils or soils with organic layers which do not provide sufficient lateral support, columns can be formed by injecting a hydraulic binder into the column material (stones, gravel) during installation. In the case of grouted stone columns, a grout is injected during the compaction of the stones/gravel. A further development of this technique uses premixed materials (grout + gravel) or concrete, which are installed by using a bottom feed vibrator. In Germany such columns can be applied in soft soils, which have an undrained shear strength of at least 15 kN/m^2 (*Deutsches Institut für Bautechnik 2002)*. Layers with an undrained shear strength between 8 and 15 kN/m^2 are acceptable, provided that the thickness of such layers is smaller than 1 m.

3.2 *Design load transfer mat*

Compared to stone columns, grouted stone columns or concrete columns have a much higher strength and stiffness. The art of the stress redistribution can be modelled in various ways. Figure 2 shows, for example, a system consisting of several arching shells.

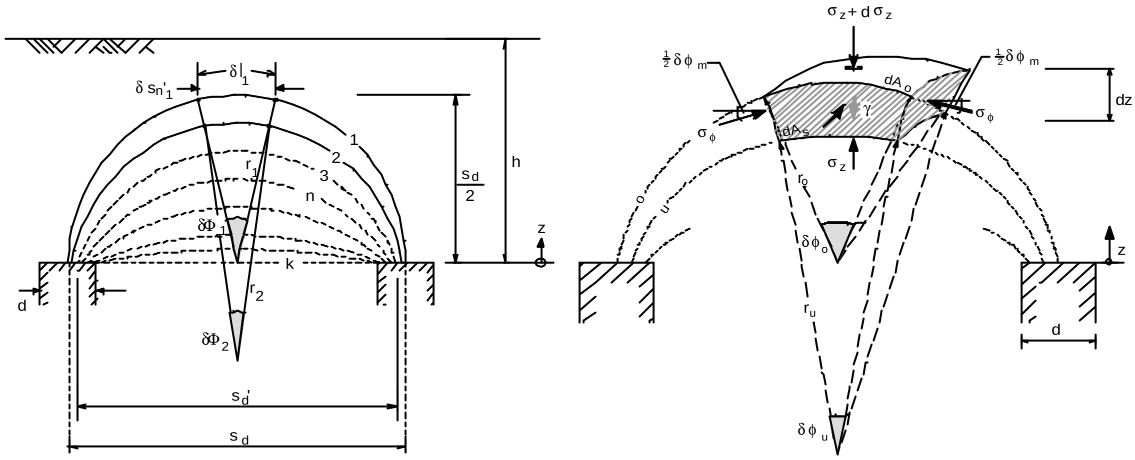


Figure 2. Theoretical arching model (after *Zaeske & Kempfert 2002)*

This model leads to a differential equation, which is a function of the vertical stresses σ_z [z] in the arching system:

$$-s_z \cdot dA_u + (s_z + ds_z) \cdot dA_o - 4 \cdot s_F \cdot dA_s \cdot \sin\left(\frac{dF_m}{2}\right) + ? \cdot dV = 0 \qquad (4)$$

For the areas above the arches a load depending stress distribution is assumed. The effective stress on the soft soil stratum σ_{zo} results from the limiting value consideration z $\rightarrow$ 0 with t = height of the load depending arch:

$$s_{zo} = l_1^{\,c} \cdot \left(g + \frac{p}{h}\right) \cdot \left(h \cdot \left(l_1 + t^2 \cdot l_2\right)^{-c} + t \cdot \left(\left(l_1 + \frac{t^2 \cdot l_2}{4}\right)^{-c} - \left(l_1 + t^2 \cdot l_2\right)^{-c}\right)\right) \qquad (5)$$

$$\chi = \frac{d \cdot (K_{krit} - 1)}{l_2 \cdot s_d},\; l_1 = \frac{1}{8} \cdot (s_d - d)^2,\; l_2 = \frac{s_d^{\,2} + 2 \cdot d \cdot s_d - d^2}{2 \cdot s_d^{\,2}},\; K_{krit} = \tan^2\left[45° + \frac{j'}{2}\right] \qquad (6)$$

Simplified σ_{zo} can also be derived from dimensionless diagrams (*Zaeske & Kempfert 2002)*. In figure 3 analytically calculated stresses are compared with those resulting from model tests.

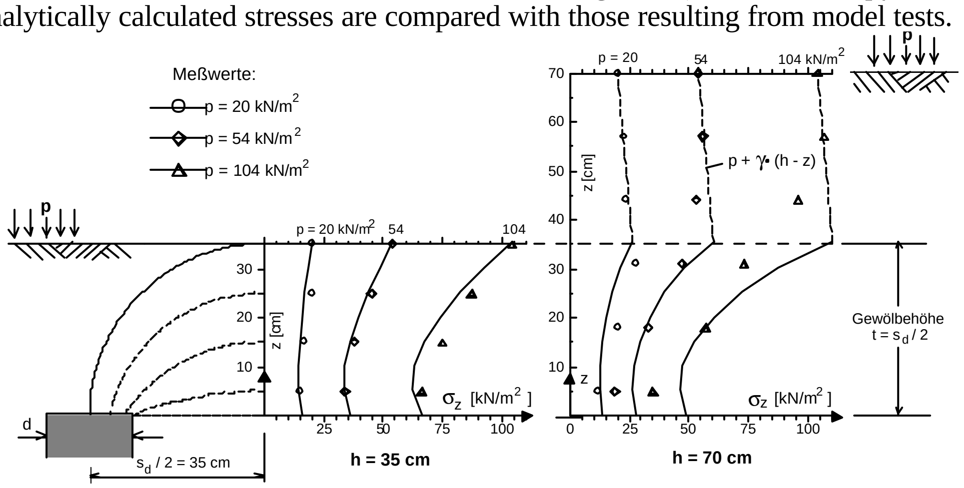


Figure 3. Stresses in bearing layer: theoretical vs. tests (height of the bearing layer h = 35 und 70 cm)

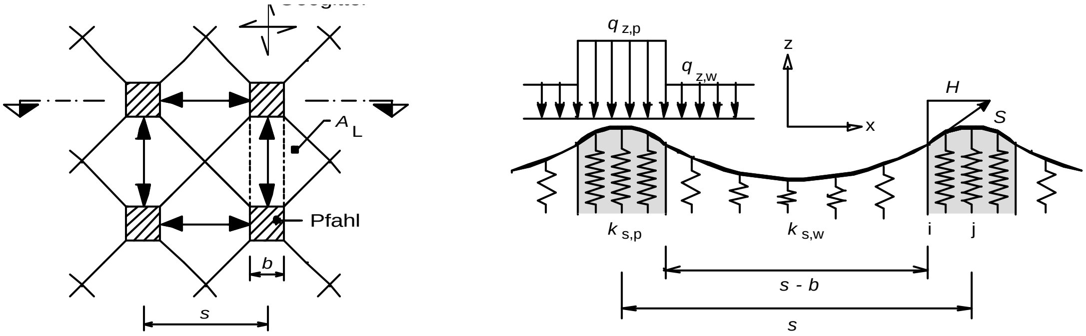


Figure 4. Horizontal bearing system for membrane effect

The loading of the reinforcement is expressed by the differential equation of the elastic supported cable, in which the vertical displacement *z* and the horizontal force *H* according to fig. 4 are the unknown variables:

$$\frac{d^2z}{dx^2} = \frac{q_z}{H} + \frac{k_s \cdot z}{H} \quad \text{with } H = \frac{2 \cdot \int_0^i \sqrt{1+z_W'^2}\,dx + 2 \cdot \int_i^j \sqrt{1+z_P'^2}\,dx - l_0}{2 \cdot \int_0^i \left(1+z_W'^2\right)dx + 2 \cdot \int_i^j \left(1+z_P'^2\right)dx} \cdot J \qquad (7)\ (8)$$

Finally the loading of the reinforcement can be calculated directly as a function of the elongation of the geosynthetic (dimensionless diagrams are also available, see *Zaeske & Kempfert (2002))*:

$$S[x] = E_{S,k}[x] = e[x]/J = H \cdot \sqrt{1+z'^2[x]} \qquad (9)$$

4 GEOTEXTIL-ENCASED COLUMNS (GEC)

4.1 *Description*

This new method is a further development of well-known column-type techniques such as stone columns. With this method sand columns, which are encased by a geosynthetic, are installed into a bearing layer. In contrast to conventional techniques, encased sand columns can be used as a ground improvement and bearing system in very soft soils, for example peat or sludge with undrained shear strengths $c_u \leq 2$ kN/m². Whereas in the excavation method a steel pipe is vibrated into the ground after which the soil is removed with an auger, in the displacement method a steel pipe with 2 base flaps (which close upon contact with the soil) is vibrated down displacing the soft soil (fig. 5). Column installation by means of a vibrator is also used (see *Sidak & Strauch 2003)*.

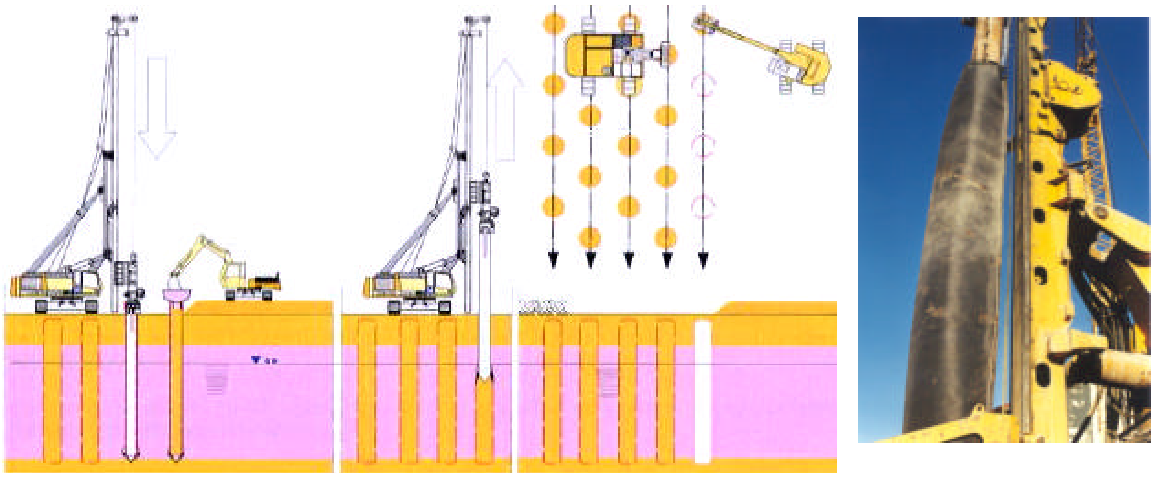


Figure 5. Conventional displacement method (left) and installation with a vibrator (right)

4.2 *Design*

The horizontal support of the soil $s_{h,s,tot}$, which essentially depends on the vertical pressure on the soft soil $s_{v,s}$, is reduced due to the radial supporting effect of the geosynthetic coating $s_{h,geo} = f(F_R)$. The vertical load $\sigma_{v,B}$ on the soft soil reduces due to the arching effect in the embankment or the load transfer mat and the stresses on the columns $\sigma_{v,S}$ increases. Generally, an analytical, axial symmetric model (according to the unit cell concept; fig. 6) after *Raithel (1999)* and *Raithel & Kempfert (2000)* is used for calculating and designing a geotextile-encased column foundation.

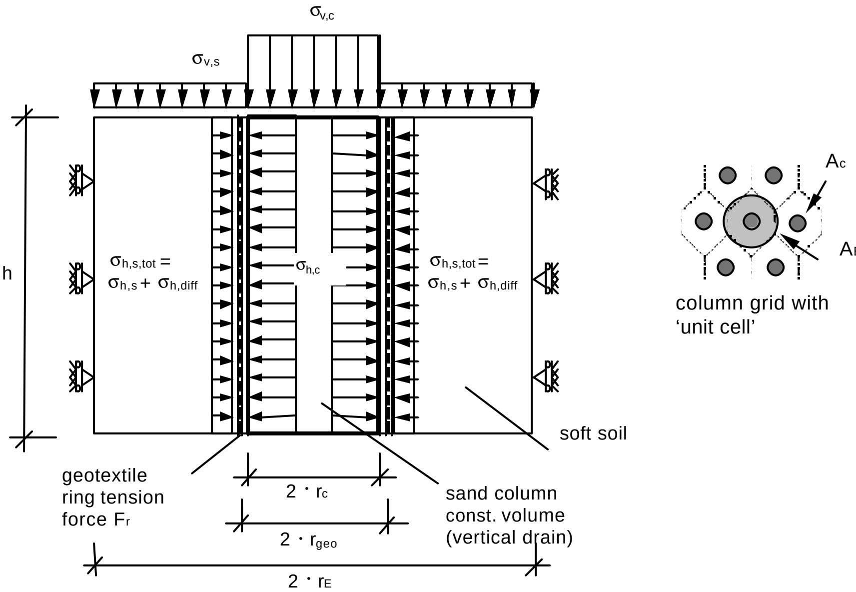


Figure 6. Calculation model 'geotextile encased sand column'

The geotextile casing (radius r_{geo}) has a linear-elastic behaviour (stiffness J), whereby the ring tensile force F_R can be transformed in a horizontal stress $\Delta\sigma_{h,geo}$, which is assigned to the geotextil:

$\Delta F_R = J \cdot \Delta r_{geo}/r_{geo}$ and $\Delta\sigma_{h,geo} = \Delta F_R/r_{geo}$ (10) (11)

By the use of the separate horizontal stresses a difference horizontal stress can be defined, which represents the partial mobilisation of the passive earth pressure in the surrounding soft soil. The stress difference leads to an expansion of the column. The horizontal deformation Δr_c and the settlement of the soft soil s_s (oedometric modulus $E_{oed,s}$) are calculated according to *Ghionna & Jamiolkowski (1981)*. Assuming equal settlements of column and soft soil, the following calculation equation can be derived:

$$\left\{ \frac{\Delta s_{v,s}}{E_{oed,s}} - \frac{2}{E^*}\cdot\frac{n_s}{1-n_s} \left[\begin{matrix} K_{a,c}\cdot\left(\frac{1}{a_E}\cdot\Delta s_0 - \frac{1-a_E}{a_E}\cdot\Delta s_{v,s} + s_{v,0,c}\right) - \\ K_{0,s}\cdot\Delta s_{v,s} - K_{0,s}^*\cdot s_{v,0,s} + \frac{(r_{geo}-r_c)\cdot J}{r_{geo}^2} - \frac{\Delta r_c\cdot J}{r_{geo}^2} \end{matrix} \right] \right\}\cdot h = \left[1 - \frac{r_c^2}{(r_c+\Delta r_c)^2}\right]\cdot h \quad (12)$$

$$\Delta r_c = \frac{K_{a,c}\cdot\left(\frac{1}{a_E}\cdot\Delta s_0 - \frac{1-a_E}{a_E}\cdot\Delta s_{v,s} + s_{v,0,c}\right) - K_{0,s}\cdot\Delta s_{v,s} - K_{0,s}^*\cdot s_{v,0,s} + \frac{(r_{geo}-r_c)\cdot J}{r_{geo}^2}}{\frac{E^*}{(1/a_E - 1)\cdot r_c} + \frac{J}{r_{geo}^2}} \quad (13)$$

with $$E^* = \left(\frac{1}{1-n_s} + \frac{1}{1+n_s}\cdot\frac{1}{a_E}\right)\cdot\frac{(1+n_s)\cdot(1-2n_s)}{(1-n_s)}\cdot E_{oed,s} \quad (14)$$

This equation can be solved by an iteration process. The oedometric modulus $E_{oed,s}$ of the soil should be introduced stress dependent. In the displacement method the effect of the soil displacement has to be taken into account.

4.3 *General experiences*

Since 1995 geotextile-encased columns have been applied in 15 projects, especially for the construction of road and railway embankments. According to the executed measurements, the bearing and settlement behaviour of these foundations is as planned.

To assess the effectiveness of the encased columns in relation to conventional column foundations, the results of tests *(Raithel 1999)* and executed projects are compared with published results of stone column foundations (fig. 7). The soil improvement factors of encased columns are situated generally above the regression curve representing the stone column foundations and show a significant increase with growing geotextile stiffness.

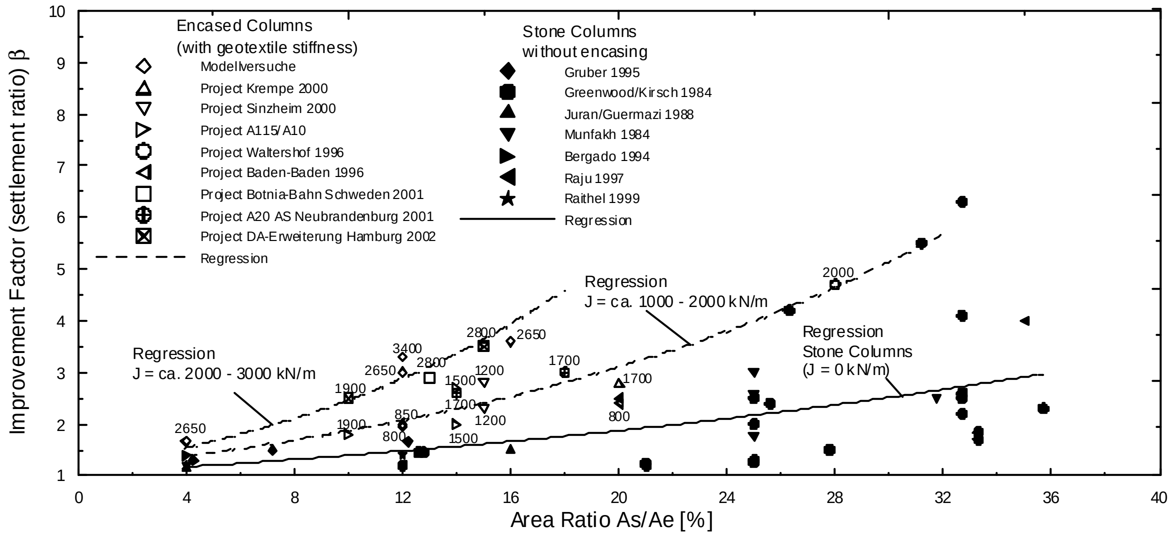


Figure 7. Soil improvement factors depending on area replacement ratio

4.4 *The extension of the airplane dockyard Hamburg-Finkenwerder*

The plant site of the airplane dockyard (EADS) in Hamburg-Finkenwerder was enlarged by approx. 140 ha for new branches of production, in particular for the production of the new Airbus A 380. The area extension was carried out by enclosing the polder (marsh or wetland) with a 2.4 km long dike. The situation is shown in figure 8.

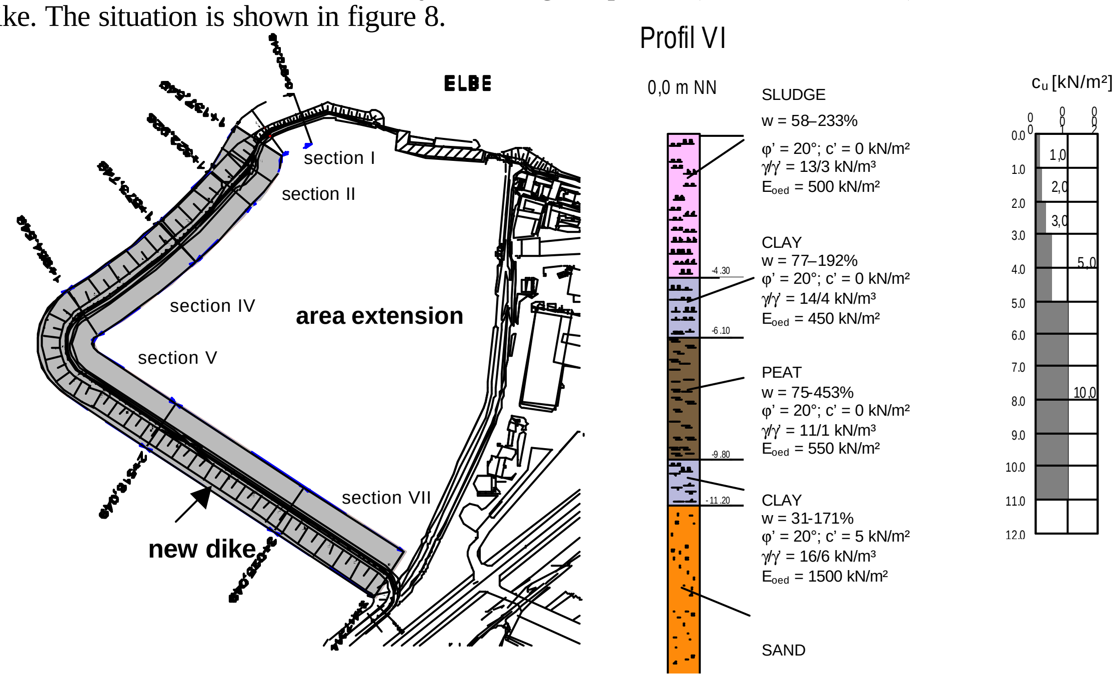


Figure 8. Concept to reclaim land by the construction of a polder and soil profile (Section VI)

A temporary enclosure was necessary, because it was only possible to fill up the first sand layers (until 3.0 m over sea level) in the area under buoyancy. Based on an alternative proposal, the necessary dike foundations were realized by about 60,000 geotextile encased sand columns (System Möbius GEC) with a diameter of 80 cm, which were installed into the bearing layer, which is present at depths between 4 an 14 m below the base of the dike footing.

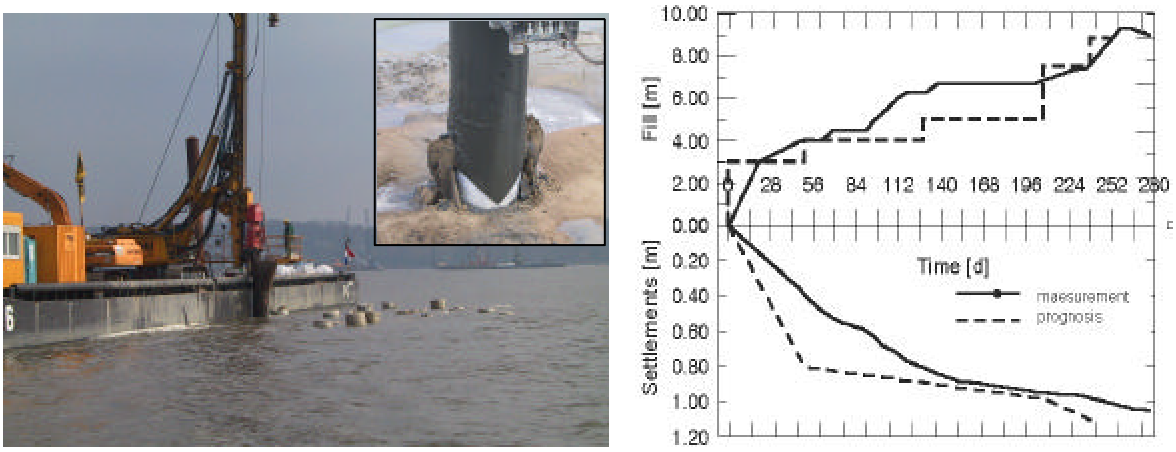


Figure 9. Installation by vibro displacement from pontoon and measured settlements in section VI

The sand-filled columns are encased by the seamless, circular-woven geotextile Ringtrac®, which is made of polyester threads. The stiffness of the geotextile casing was between J = 1,700 and 2,800 kN/m. The maximum high tensile force of the geotextile varied between 100 and 400 kN/m over the cross section of the dike. For this project, the ratio of the column area A_C to the influence area A_E (A_C/A_E) was between 0.10 and 0.20. More details are shown in *Kempfert & Raithel (2002).*

The majority of the columns were installed using equipment operating from offshore pontoons (110 × 11 m) to cope with the tidal fluctuation (3.5 m water level difference), as shown in figure 9. At low tide, work continued with the pontoons resting directly on the soft soil. After installation, the column heads were stabilized by putting sand between the columns.

On the basis of the measurements it can be shown (fig. 9), that the real soil conditions were better than the soil parameters given in the tender documents, especially with regard to the consolidation behaviour. Due to high effectiveness of the foundation system, the dike could be constructed in approx. 9 months to about 7 m height. Therefore, the required safety of the dike corresponding to high water level could be reached after 39 weeks.

5 CSV-METHOD

Combined soil stabilization with vertical columns (CSV) is a technique, whereby small diameter columns consisting of a binder or binder mixture are installed in a close grid. By hardening of the stabilization material rigid columns can be formed. In Germany, a dry cement-sand-mixture as binder is used, which is installed into the soft soil by the displacement method using a continuous auger (so-called Coplan-Stabilization-Method, fig. 10).

Basic guidelines for the calculation and design are given in *DGGT (2002).* For the verification of the safety against fracture of the column, it is generally assumed, that all loads are carried by the CSV columns. The characteristic resistance of the columns $R_{c,K}$ is usually calculated by the unconfined compressive-strength $q_{u,k}$ (A_C = column area):

$$R_{c,K} = A_C \cdot q_{u,k} \tag{15}$$

The total settlement results from the compression of the single columns s_Z^{ES}, the settlement of the single column s_B^{ES} and the setttlement due to the group effect s_G. *(DGGT 2002):*

$$s = s_Z^{ES} + s_B^{ES} + s_G \tag{16}$$

The bearing capacity of the columns has to be verified by means of load testing.

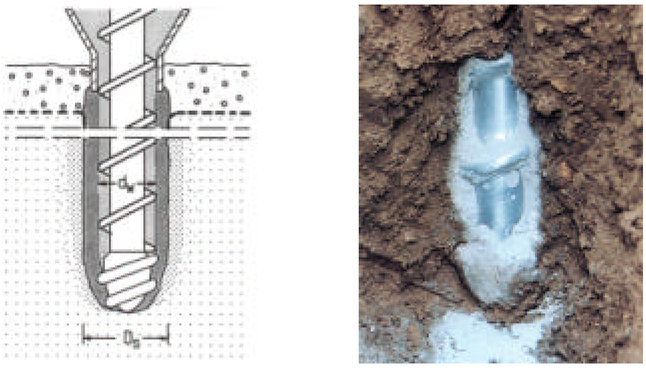


Figure 10. CSV-columns (after Bauer Spezialtiefbau)

6 LIME AND LIME CEMENT COLUMNS (DEEP SOIL MIXING)

6.1 *Description*

Lime and lime cement columns are installed using the deep soil mixing technique, in which a hardening binder such as lime, cement or a mixture of lime and cement is mixed with the soil using mixing tools. This technique was developed and put into practice in the middle of 1970's independently in Sweden and Japan. It is distinguished between dry mixing and wet mixing. In dry mixing a mixing tool is penetrated to the desired depth after which during retrieval a dry binder (usually a lime cement mixture) is injected into the soft soil using compressed air. This binder is mixed with the soil (fig. 11). Since no water is added, the soil should have a water content of at least 20%. In wet mixing generally a cement slurry is added to the soil mechanically.

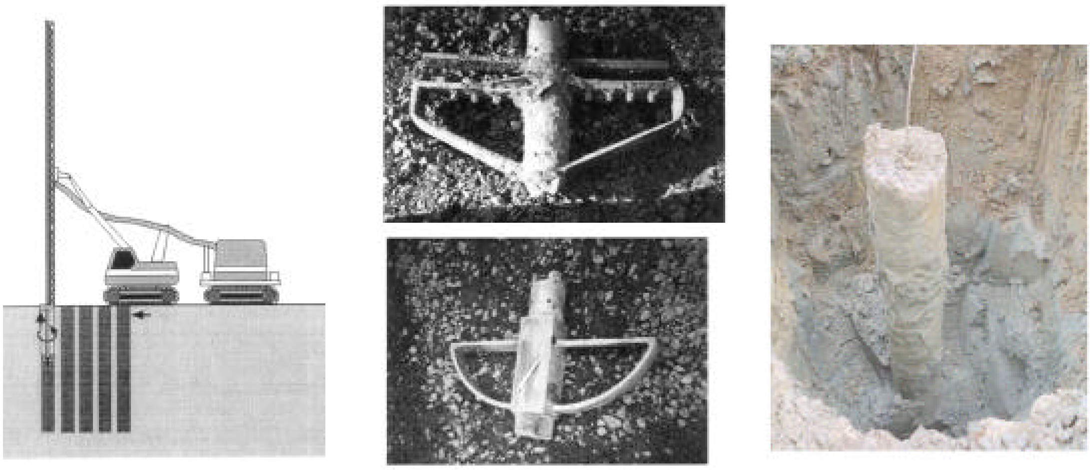


Figure 11. Basic principle of dry deep soil mixing, mixing tools and excavated column

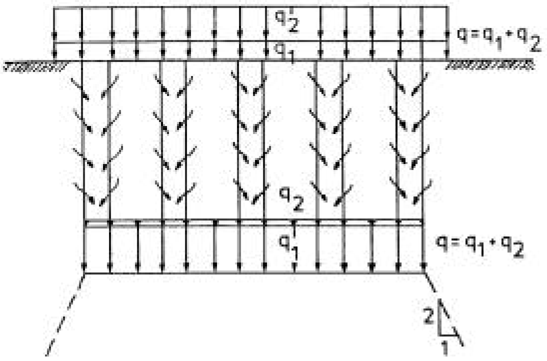
6.2 *Design*

The construction load is carried partly by the lime cement columns and partly by the unstabilized soft soil between the columns.

The settlement of the composite ground can be calculated according to the analytical method of the *Swedish Geotechnical Society (1997)*, see fig. 12.

Settlements within the area stabilized by lime cement columns are calculated by dividing the soil profile into characteristic strata. Settlement in the columns S_1 is calculated in accordance with equation (17), where Δh = stratum thickness, q_1 = load on column, a = ratio of total column area to total area of reinforced soil and E_{col} = Young's modulus of column. Settlement in the unstabilized soil S_2 is calculated in accordance with equation (18), where q_2 = load on unstabilized soil and E_{oed}= compression modulus of unstabilized soil.

A first calculation is made by assuming that $q_1 = q_{1max}$. The calculated settlement S_1 in the columns is compared with the calculated settlement S_2 in the unstabilized soil. If $S_1 > S_2$, a load transfer is performed by gradually reducing q_1 and correspondingly increasing q_2, so that finally $S_1 = S_2$. The calculated settlement S_m is then equal to S_1 and S_2. If the soil is normally consolidated, S_m can be calculated from equation (19). If however $S_1 < S_2$, the columns cannot take any more load, and the settlement S_1 which occurs is equal to the calculated settlement S_2 in the unstabilized soil.



$$s_1 = \sum \frac{Dh}{a} \cdot \frac{q_1}{E_{col}} \quad (17)$$

$$s_1 = \sum \frac{\Delta h}{1-a} \cdot \frac{q_2}{E_{oed}} \quad (18)$$

$$s_m = \Sigma \frac{Dh \cdot q}{a \cdot E_{col} + (1-a) \cdot E_{oed}} \quad (19)$$

Figure 12. Principle of load distribution in ground improvement with lime cement columns

This calculation method is similar to conventional settlement calculation methods, which use a mean stiffness value of the composite ground. It is clear, that only a rough estimation of the settlement behaviour can be obtained. The use of finite element calculation methods is therefore useful.

6.3 *General experiences*

Research and practical applications in Europa have shown, that organogenic and organic soils can also be stabilized with lime cement columns *(Holm 2002, EuroSoilStab 2002). Holm, Andréasson, Bengtsson & Eriksson (2002)* reported a successful application of lime cement columns in a very soft organic soil (gyttja) und clays for the stabilization of a low railway embankment in Sweden. A binder consisting of unslaked lime and cement in an amount of 120 - 150 kg/m^3 was used. Despite an organic content of up to 20% and an embankment height of only 1.4 m, a settlement reduction factor of 5 at low train speeds and of up to 15 at train speeds of 200 km/h was achieved.

More positive experiences with lime cement columns in very soft cohesive soils with organic admixtures are reported for instance by *Sondermann & Wehr (2002)*.

During a test in the Netherlands, where lime cement columns with a binder of lime and cement in a ratio of 20%/80% and in an amount of 200 kg/m^3 were installed in very soft organic soils, however, he necessary strength was not reached *(RWS Dienst Weg- en Waterbouwkunde 2001)*.

6.4 *Test site Hude-Nordenham (Germany)*

In 2002, the dry deep soil mixing method (designated as Trocken-Einmisch-Technik TET) was applied in Germany for the first time. Experimental research was carried out on a 5 test embankments (each 30 m long), designated as TS0 up to TS4. Lime cement columns of approx. 60 cm diameter and consisting of 10% lime and 90% cement were installed in various patterns and lengths (fig. 13). In test field TS0 no ground improvement was carried out. The sub soil consists of 10 to 11 m soft holocene clay with some peat.

The measurements during the observation period showed no clear improvement of the settlement behaviour, however, the evaluation of the measurements of the dynamic performance of the sub soil showed an increase of the dynamic bearing behaviour due to the lime cement columns *(Katzenbach, Ittershagen, Savidis & Wesenmüller 2003)*.

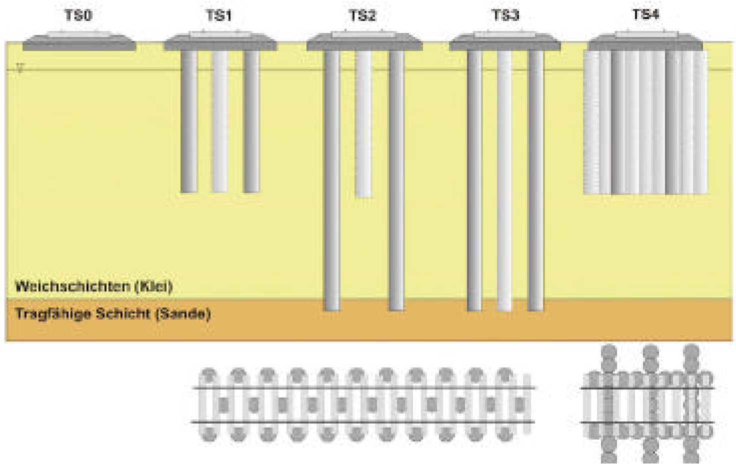


Figure 13. Test site Hude-Nordenham (after *Katzenbach, Ittershagen, Savidis & Wesenmüller 2003*)

The interpreted results of the vertical acceleration measurements, which were carried out at the superstructure during the passage of 109 trains, are given in figure 14. The RMS values (*R*oot *M*ean *S*quare) of the calculated vibration velocity spectrum for a range of f < 15 Hz are plotted as a function of the train speed V_{real}.

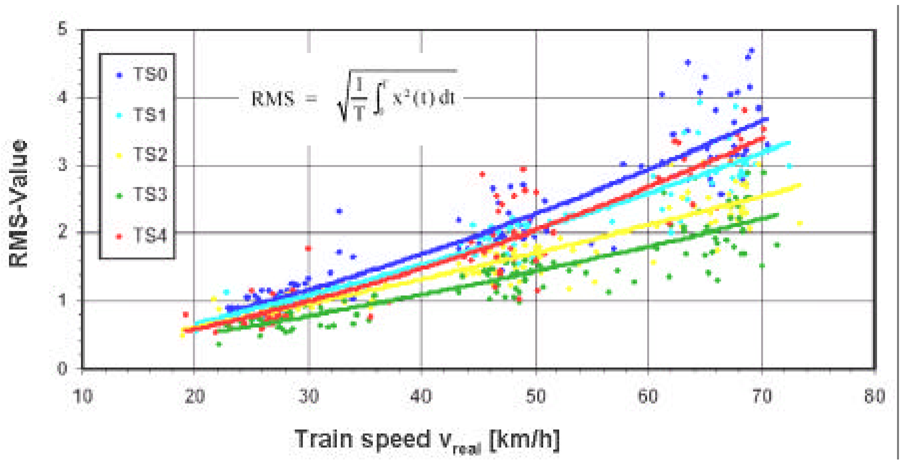


Figure 14. RMS values from acceleration measurements at superstructure Hude-Nordenham

7 CUT-MIX-INJECTION METHOD (FMI)

The cut-mix-injection method (Fräsch-Misch-Injektions-Verfahren, FMI) is a German method, by which soft soils can be cut, mixed and injected with cement slurry during one process (fig. 15). This results in rigid wall type structures with a width up to 1 m. Positive or negative experiences are known. This type of ground improvement is designed by carrying out some load tests, out of which a soil improvement factor can be deduced.

Figure 15. Cut-mix-injection method

8 INJECTION PILES

A new soil improvement and foundation system on soft soils is the use of injected micropiles. A friction-micropiled-raft foundation has successfully been realised for new buildings on soft soils to stabilize the underground and reduce the settlements. An exemplary comparison of practical applications in terms of measured settlements of a raft foundation with the friction-micropiled-raft foundation on normally consolidated soft soils has proven the effectiveness of the new foundation system (*Kempfert & Böhm 2002*), see figure 16.

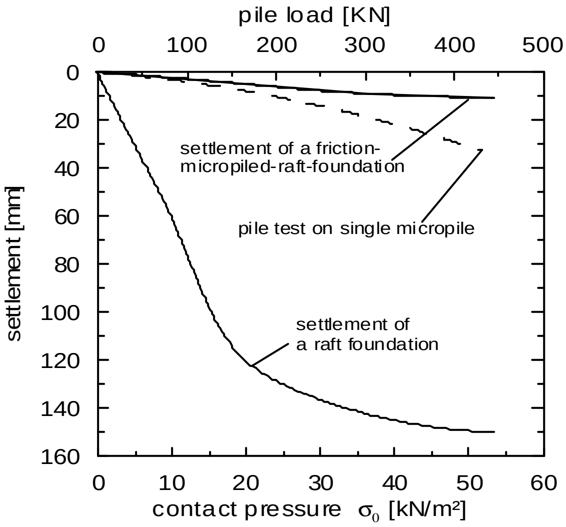


Figure 16. Settlements of raft foundation and friction-micropiled-raft foundation

The effectiveness of the friction-micropiled-raft foundation systems is a result of the pre-stressing of the soft soil between the piles by the injection pressures during pile installation.

9 EVALUATION OF TECHNIQUES

The discussed column-type techniques for improving soft soils are evaluated roughly in the following matrix.

	Stone columns	Grouted stone columns	Geotextil encased columns	CSV	Lime cement columns	FMI	Injection piles
Application possibilities	--	-	+	-	0	0	0
Dynamical behaviour	-	+	0	0	0	+	+
Experiences	0	+	+	-	-	+	0
Long-term stability	0	+	+	+	0	+	+
Construction risks	-	0	0	+	0	0	+
Construction time	+	0	+	+	+	0	0
Costs	+	-	0	-	0	--	-
Calculation/Design method	0	+	0	-	-	0	0

REFERENCES

Bergado, D. T., Chai, J. C., Alfaro, M. C. & Balasubramaniam, A. S. 1994. Improvement Techniques of Soft Ground in Subsiding and Lowland Environment. Rotterdam/Brookfield: Balkema.

Deutsches Institut für Bautechnik. 2002. Allgemeine bauaufsichtliche Zulassung für Vermörtelte Stopfsäulen (VSS), Fertigmörtel Stopfsäulen (FSS) und Betonstopfsäulen (BSS).

DGGT Deutsche Gesellschaft für Geotechnik e.V. 2002. Merkblatt für die Herstellung, Bemessung und Qualitätssicherung von Stabilisierungssäulen zur Untergrundverbesserung, Teil I - CSV-Verfahren.

EuroSoilStab. 2002. Development of design and construction methods to stabilise soft organic soils; Design Guide Soft Soil Stabilisation. EC Project BE 96-3177.

FGSV Forschungsgesellschaft für Straßenwesen. 1979. Merkblatt für die Untergrundverbesserung durch Tiefenrüttler. Köln: FGSV Verlag.

Ghionna, V. & Jamiolkowski, M. 1981. Colonne di ghiaia, X Ciclo di conferenze dedicate ai problemi di meccanica dei terreni e ingegneria delle fondazioni metodi di miglioramento dei terreni; Politecnico di Torino Ingegneria, atti dell'istituto di scienza delle costruzioni, n°507.

Goughnour, R. R. & Bayuk, A. A. 1979. Analysis of Stone Column-Soil Matrix Interaction under Vertical Load. *Colleque Int. sur le Renforcement des Sols*, Vol. 1: 271-277. Paris.

Holm, G. 2002. Deep Mixing - Research in Europe. Deep Mixing Work Shop 2002 in Tokyo.

Holm, G., Andréasson, B., Bengtsson, P-E., Bodare, A. & Eriksson, H. 2002. Mitigation of Track and Ground Vibrations Induced by High Speed Trains at Ledsgård, Sweden. Swedish Deep Stabilization Research Centre. Report 10, Linköping.

Katzenbach, R.; Ittershagen, M.; Savidis, S.; Wesemüller, H. 2003. Großversuche zur optimierten Baugrundverbesserung unter Verkehrswegen auf weichem Untergrund. *Darmstädter Geotechnik Kolloquium 2003*.

Kempfert, H.-G. & Raithel, M. 2002. Experiences on Dike Foundations and Land Fills on Very Soft Soils. Technical Committee TC 36 Soft Soils Foundation Engineering. *International Symposium on soft soils foundation engineering in Mexico 2002*.

Kempfert, H.-G. & Böhm, F. 2003. Experience with friction-micropiled-raft foundation on soft soils. *Proc. Of the European Conference on Soil Mech. and Geot. Engineering.*

Priebe, H. J. 1995. Die Bemessung von Rüttelstopfverdichtungen. *Bautechnik* 72, Heft 3: 183-191.

Raithel, M. 1999. Zum Trag- und Verformungsverhalten von geokunststoffummantelten Sandsäulen. Schriftenreihe Geotechnik Universität Gh Kassel, Heft 6.

Raithel, M. & Kempfert, H.-G. 2000. Calculation Models for Dam Foundations with Geotextile Coated Sand Columns. *Proc. International Conference on Geotechnical & Geological Engineering GeoEng 2000*. Melbourne.

Raju, V. R. 1997. The Behaviour of Very Soft Soils Improved by Vibro Replacement. Ground Improvement Conference, London.

RWS Dienst Weg- en Waterbouwkunde. 2001. Evaluatie No-Recess, Testbanen Hoeksche Waard. Dutch Ministry of Transport, Public Works and Water Management.

Sidak, N. & Strauch, G. 2003. Herstellung geotextilummantelter Kiestragsäulen mit Keller-Tiefenrüttler. *Tagungsbeiträge 4. Österreichische Geotechniktagung*: 415-433. Wien: ÖIAV.

Sondermann, W. & Wehr, W. 2002. Trockenpulver-Einmisch-Technik (TET) als Baugrundverbesserung für einen 500 m langen Hafendamm. *Baugrundtagung 2002 in Mainz*: 329-335. Essen, DGGT.

Soyez, B. 1987. Bemessung von Stopfverdichtungen. Ins Deutsche übertragen von H. Priebe. *Baumaschine + Bautechnik BMT*, April 1987: 170-185.

Swedish Geotechnical Society. 1997. Lime and Lime Cement Columns, Guide for Planning, Construction and Inspection. SGF Report 4:95E. Linköping.

Zaeske, D & Kempfert, H.-G. 2002. Berechnung und Wirkungsweise von unbewehrten und bewehrten mineralischen Tragschichten auf punkt- und linienförmigen Traggliedern. *Bauingenieur* Band 77.