

ТЕХНОЛОГИЯ УСИЛЕНИЯ ОСНОВАНИЯ ГРУНТОВЫМИ СВЯЯМИ. ПРОЕКТИРОВАНИЕ И РАСЧЕТ

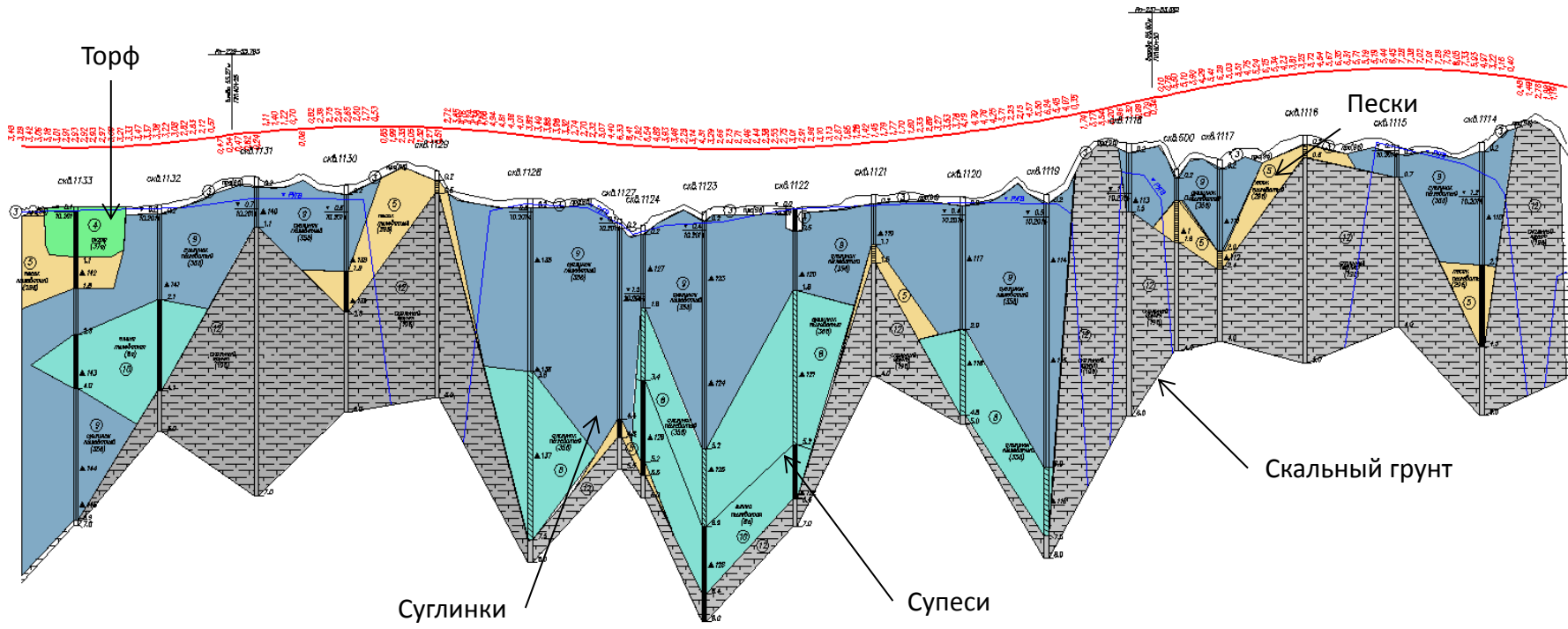
Авторы:

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СП 22.13330.2016 ОСНОВАНИЯ ЗДАНИЙ И СООРУЖЕНИЙ

Технологии усиления грунтов основания

Закрепление грунтов

- Струйный метод: Jet-grouting
- Глубинное перемешивание
 - ALLU (глубина до 2-10м),
 - Грунтоцементные сваи (DMM - Deep Mixing Methods: DSM, WRS, WRE и др.),
- Термические методы

Армирование грунтов

- Вертикальное
 - Железобетонные сваи,
 - Цементогрунтовые сваи,
 - Столбы из песчаных грунтов или щебня,
- Горизонтальное армирование
 - перераспределение нагрузки устройством гибких ростверков
- Наклонное
 - Устройство грунтовых нагелей

Jet-grouting



KLEMM
Bohrtechnik

Глубинное перемешивание

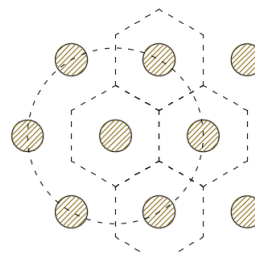


ALLU
One Step Ahead



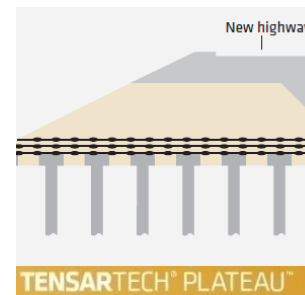
WRS метод

Грунтовые сваи/столбы

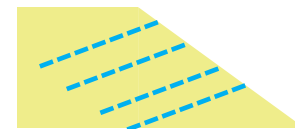


betterground

Гибкий ростверк



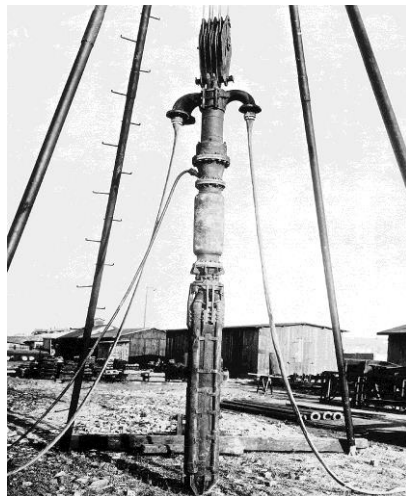
Армирование нагелями



GEOIZOL-MP

1934 год

Wilhelm L. Degen и Sergej Steuermann изобрели первый глубинный виброщуп



DEUTSCHE NORM

December 2005

DIN EN 14731

ICS 93.020

Execution of special geotechnical works –
Ground treatment by deep vibration
English version of DIN EN 14731:2005



Рис.8. Установка на базе ВВПС 32/10 для устройства вертикальных дрен и песчаных свай:

1-генератор; 2-шуховарованная лебедка; 3-трактор Т-140 или Т-180; 4-направляющая мачта; 5-вибромолот; 6-обсаженная труба

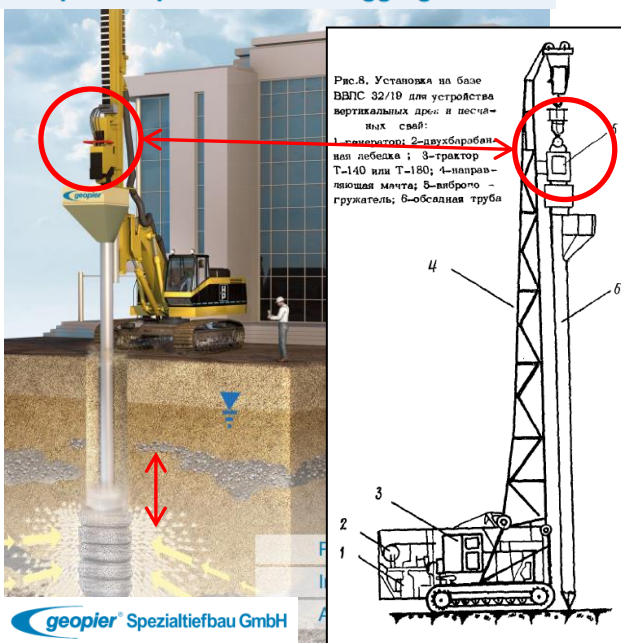


Geopier® Rammed Aggregate Piers®

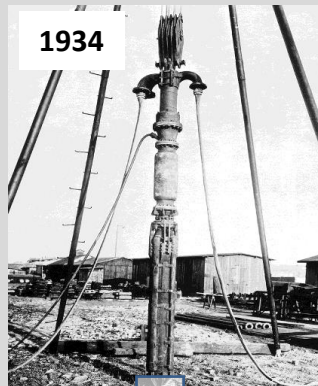


geopier® Spezialtiefbau GmbH

Geopier® Impact® Rammed Aggregate Piers®

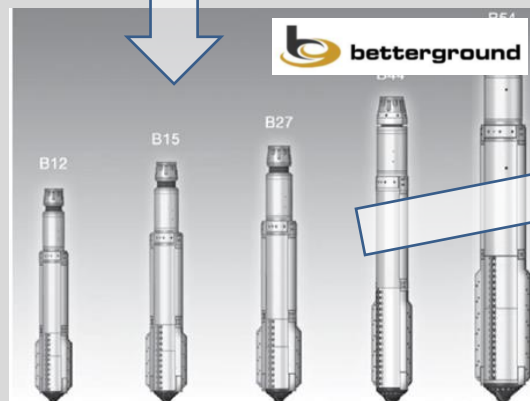


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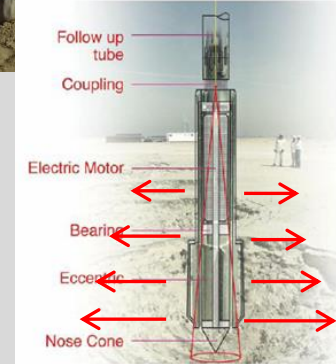


1934

ГЕОИЗОЛ
Керченский мост



Vibroflot		B12 hydraulic	B12 electric	B15 hydraulic	B15 electric
Motor Force	kW	94	90	114	105
Rotation Speed	rpm	3000	3000	3000	3000
Eccentric Force	kN	170	170	190	190
Amplitude (at tip)	mm	9	9	12	12
Diameter (above wear plates)	mm	292	292	310	310
Length	mm	2840	2840	3430	3430
Weight	kg	1530	1530	1840	2200



ГРУНТОВЫЕ СВАИ-ДРЕНЫ (по технологии глубинного виброуплотнения)

Плюсы:

- + позволяет увеличить несущую способность основания,
- + позволяет уменьшить деформации основания
- + позволяет использовать природные материалы (песок, щебень, гравий, песчано-гравийную смесь)
- + относительно низкая стоимость
- + многократно сокращает скорость стабилизации деформаций (консолидация)
- + хорошо работают на вертикальные и горизонтальные нагрузки
- + позволяет регулировать диаметр и объем материала в зависимости от задачи и грунтовых условий

Минусы:

- При использовании для усиления крайне слабых глинистых грунтов требуется проведение мероприятий по предварительному уплотнению,



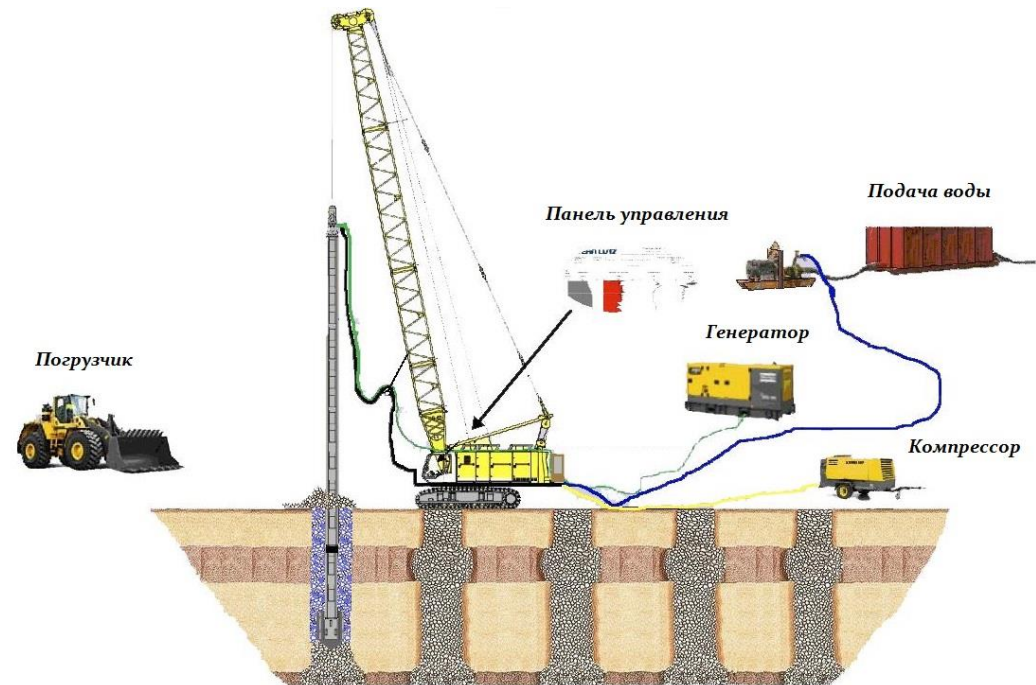
Виброколонна погружается с помощью вибрации и подачи воздуха (иногда с минимальной подачей воды для прохождения плотных слоев)



Щебень вводится через специальный привод вдоль вибропогружателя под давлением сжатого воздуха



Виброколонна совершает попеременные движения вверх и вниз для уплотнения щебня и формирования тела сваи. При этом также уплотняется и улучшается окружающий грунтовый массив.

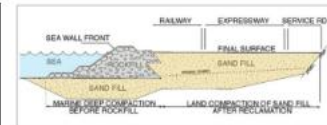




Six Mile Apartments Mount ...



Sumter Water Treat



Top Feed S
2016
America



Kaiser Permanente Hospital

Bottom Feed Stone Columns.
2004
America

[VIEW PROJECT](#)



Central Link Light Rail – Bea...

Bottom Feed Stone Columns.
2004
America

[VIEW PROJECT](#)



Cannelton Hydroelectric Pro...

Bottom Feed Stone Columns.
2011
America

[VIEW PROJECT](#)



Highway St. Petersburg – M...

Bottom Feed Stone Columns.
2014
Europe

[VIEW PROJECT](#)

f Lo...

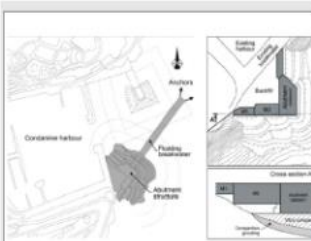
North Lantau Expressway, T...

Vibro Compaction.
1995
Asia

[VIEW PROJECT](#)

[VIEW PROJECT](#)

Top Feed S
2016
Europe



Port of Monaco

Vibro Compaction.
2000
Europe

[VIEW PROJECT](#)



Port of Patras

Bottom Feed Stone Columns.
2000
Europe

[VIEW PROJECT](#)



Hong Kong Boundary Crossi...

Bottom Feed Stone Columns.
2012
Asia

[VIEW PROJECT](#)



Boleo Marine Terminal

Bottom Feed Stone Columns.
2012
America

[VIEW PROJECT](#)

1 Feed ...

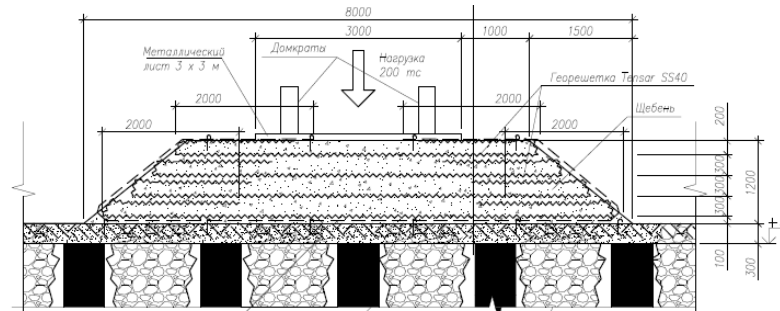
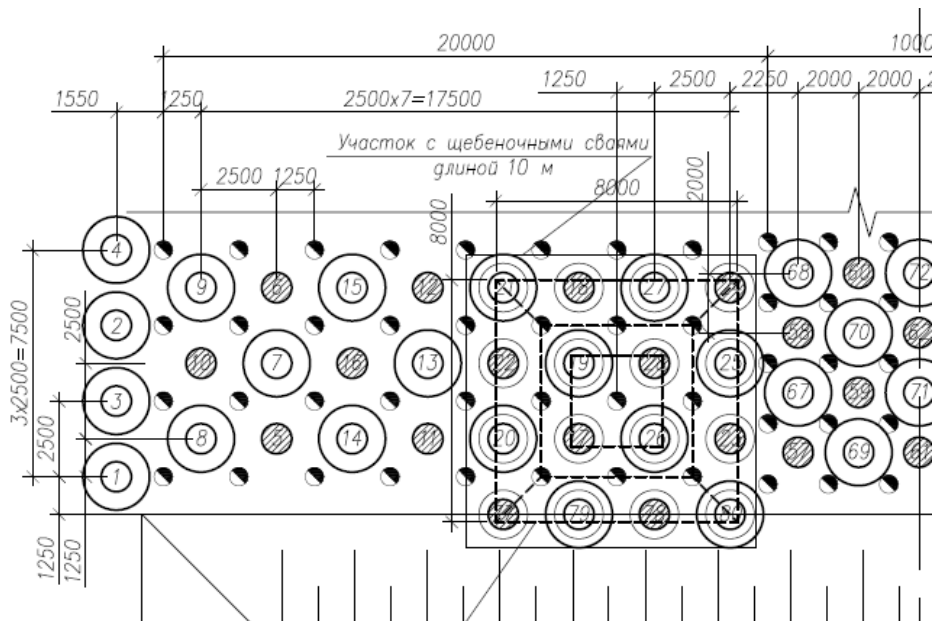
Lee Roy Selmon Expressway

Bottom Feed Stone Columns.
2003
America

[VIEW PROJECT](#)

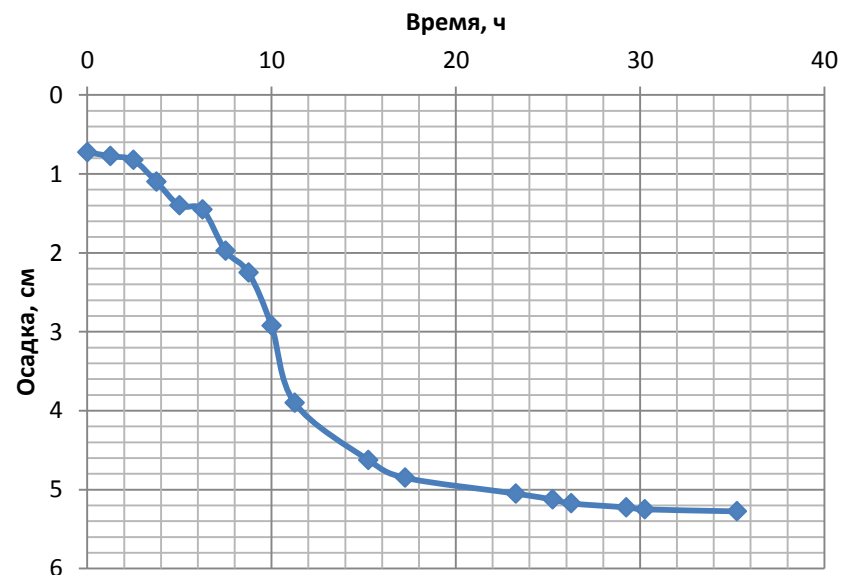
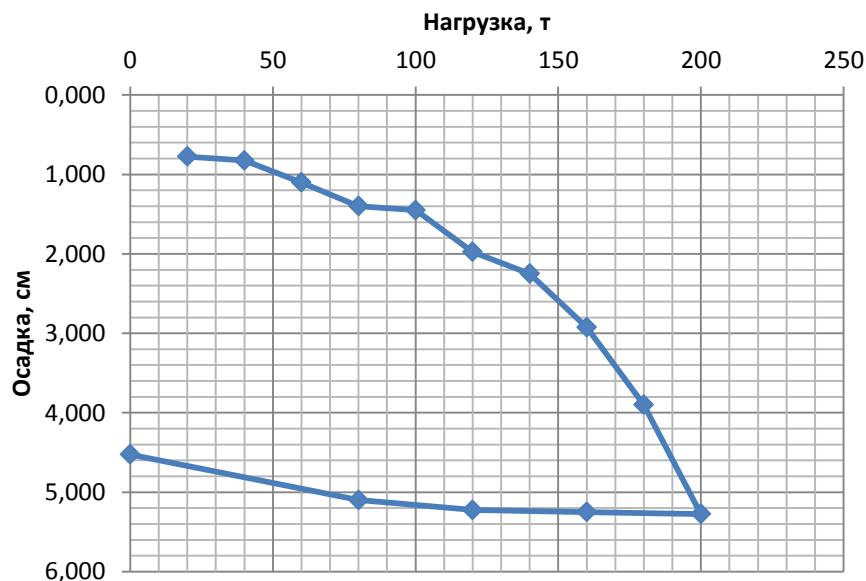
[VIEW PROJECT](#)

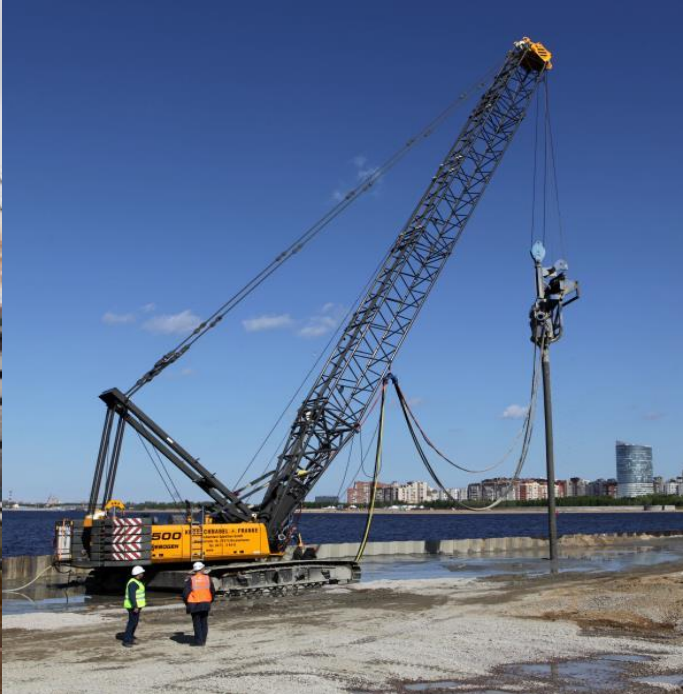
Опытный участок усиления грунтов основания автомобильной дороги А-121 «Сортавала», респ. Карелия

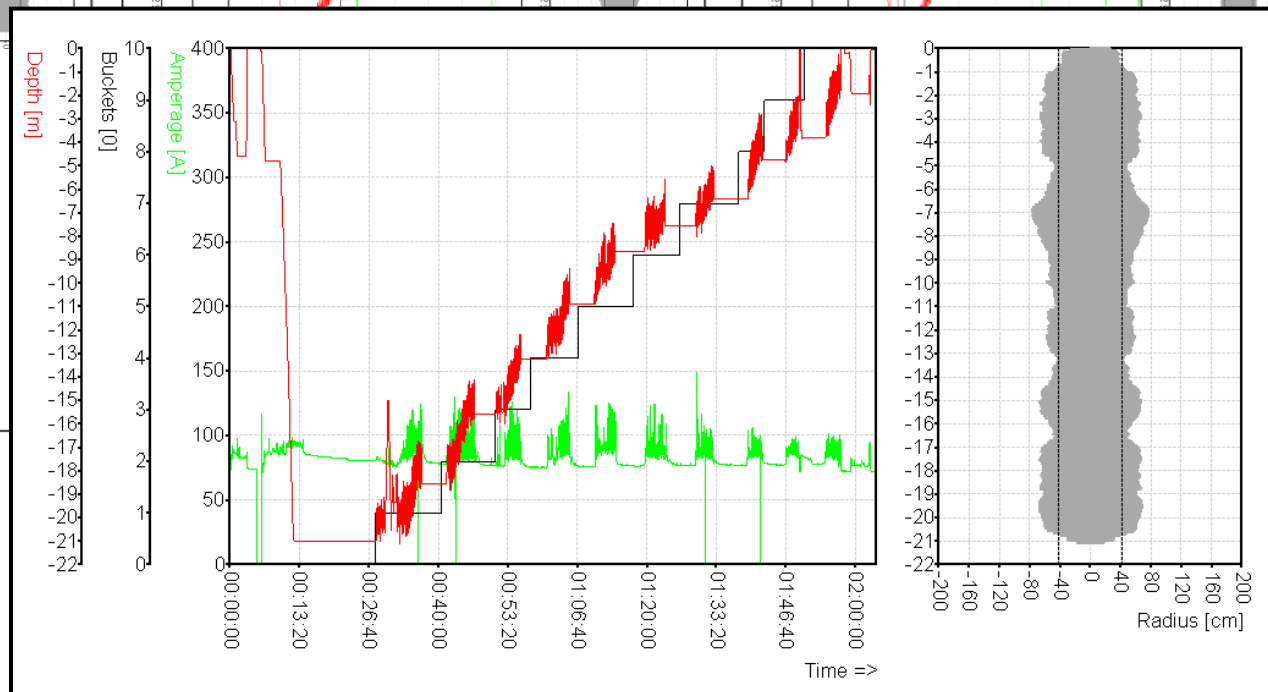
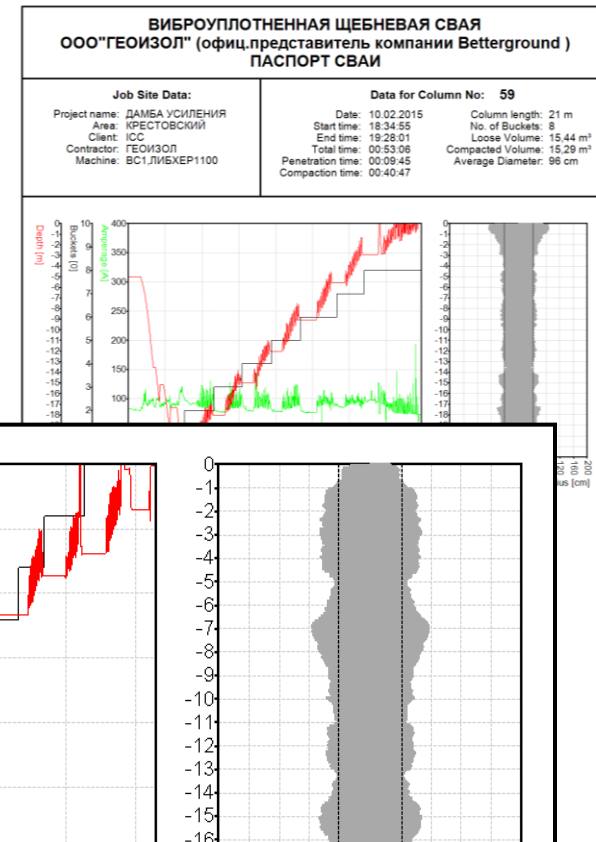
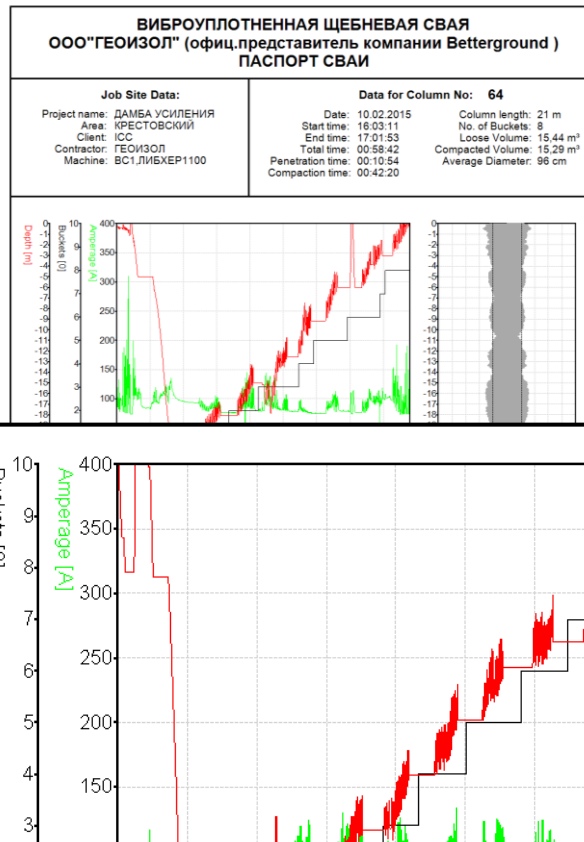
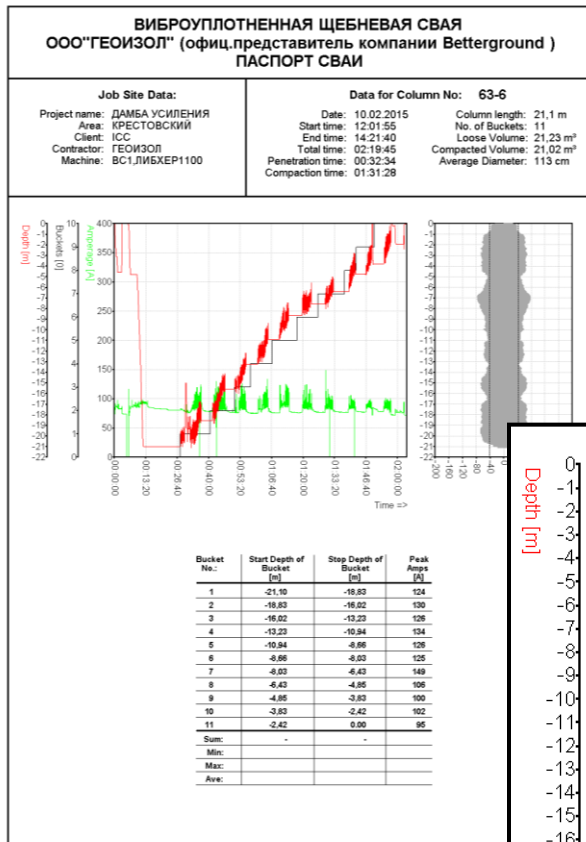


Результаты испытаний:

Нагружение производилось последовательными ступенями по 20 т,
Максимальная нагрузка на штамп 3х3м - 200 тс
Общее время испытания составило 35,5 часов,
Максимальная осадка составила 53 мм
Деформации стабилизировались и оставались неизменными на протяжении 5 часов до начала разгрузки.





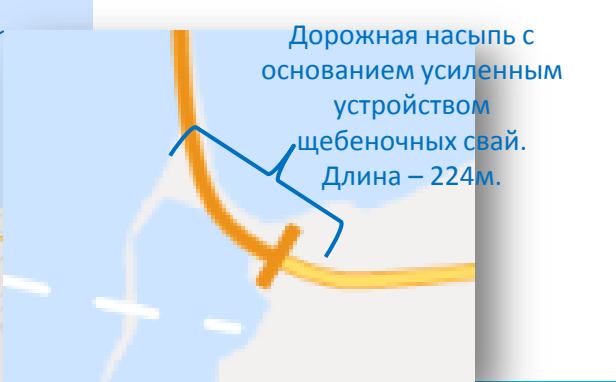
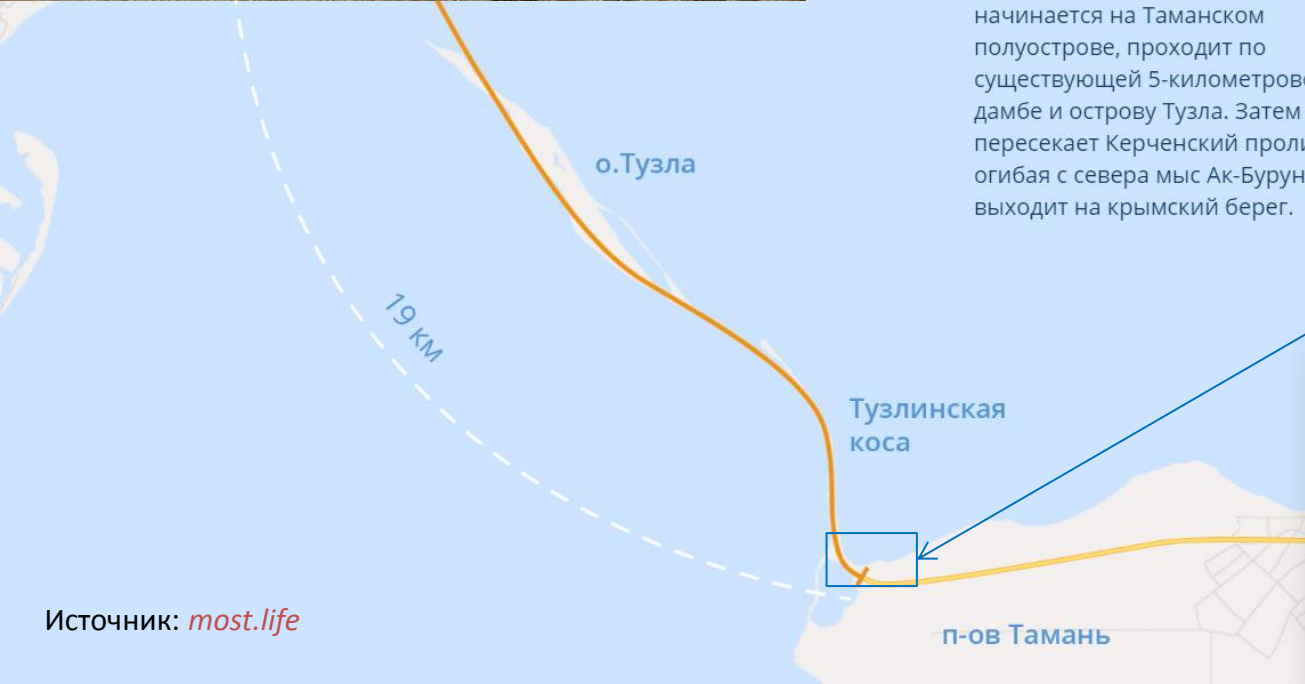


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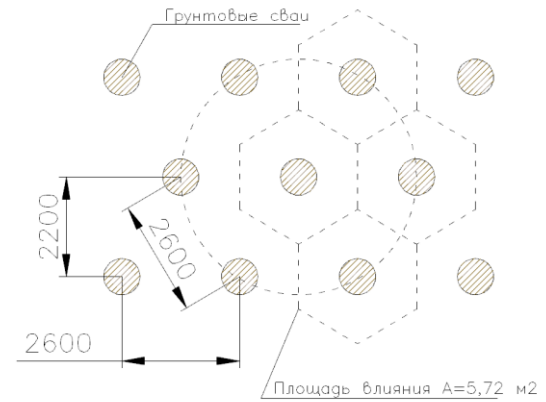
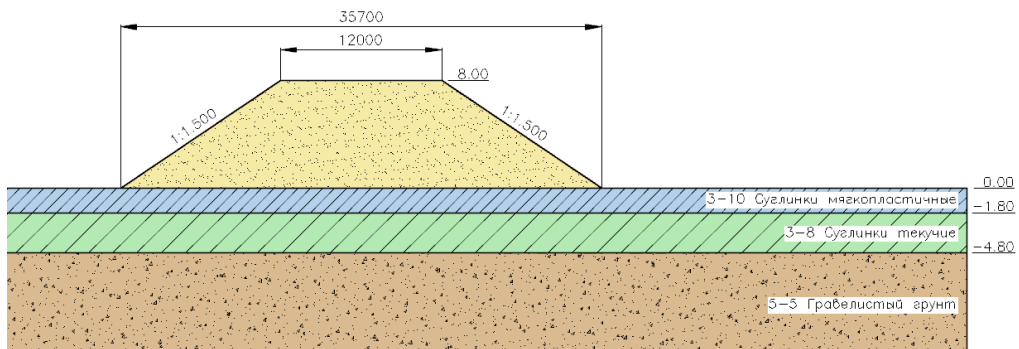
коса Чушка

Один из крупнейших мостов в России. Он состоит из параллельно расположенных автомобильной и железнодорожной трасс. Его протяженность - 19 км. Трасса начинается на Таманском полуострове, проходит по существующей 5-километровой дамбе и острову Тузла. Затем пересекает Керченский пролив, огибая с севера мыс Ак-Бурун, и выходит на крымский берег.

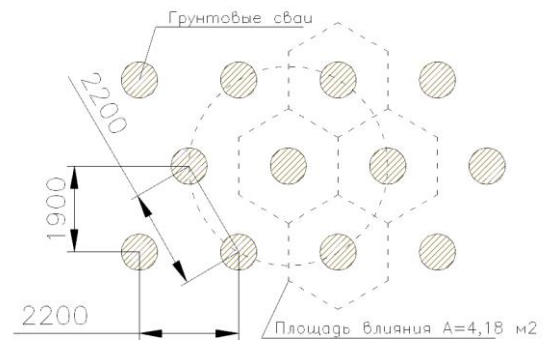
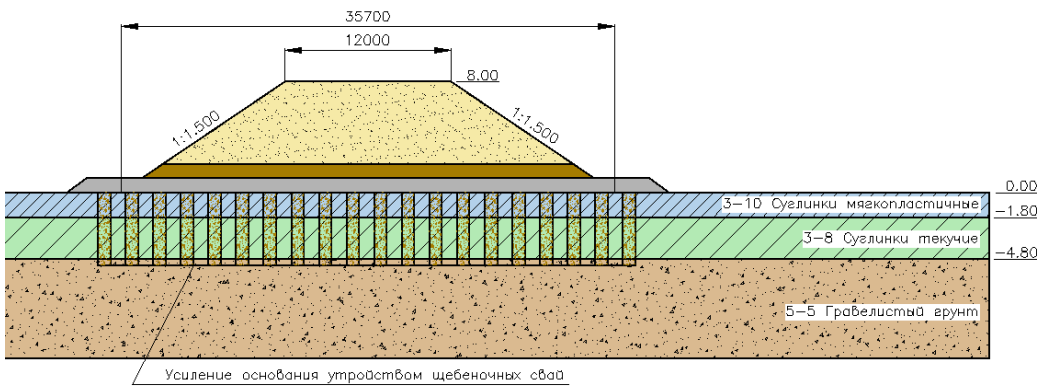


Источник: *most.life*

РАСЧЕТ ОСНОВАНИЯ УСИЛЕННОГО ГРУНТОВЫМИ СВЯЯМИ

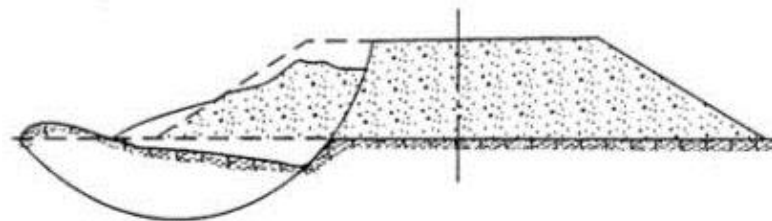


Вариант 1. Шаг 2,6x2,2
в шахматном порядке



Вариант 2. Шаг 2,2x1,9
в шахматном порядке

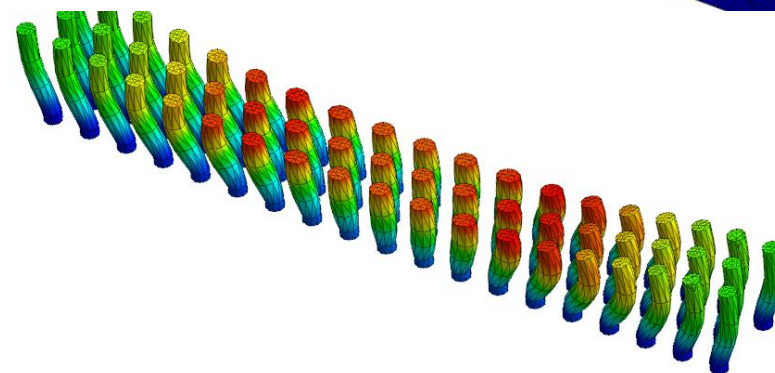
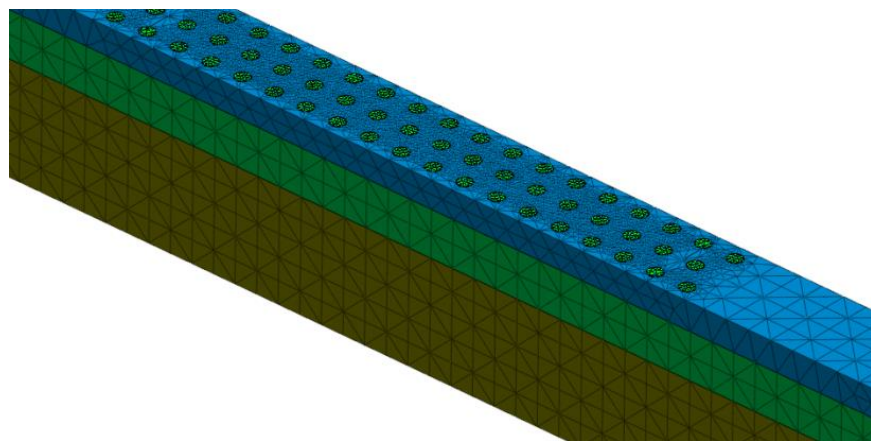
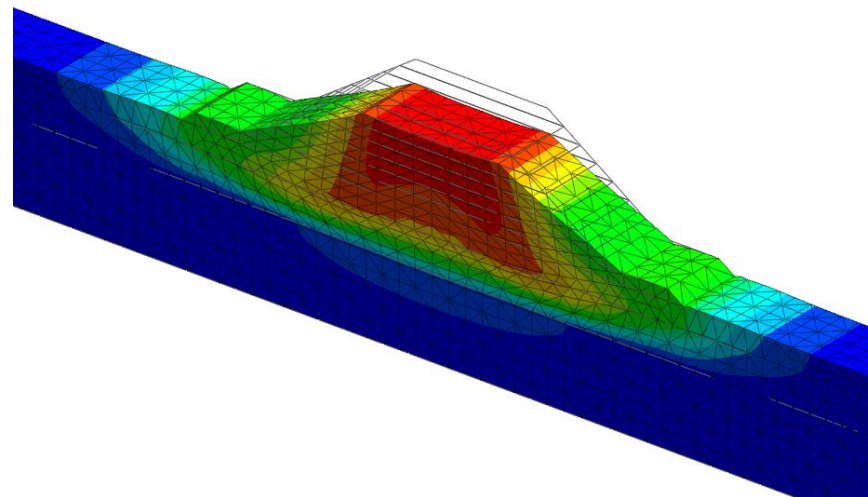
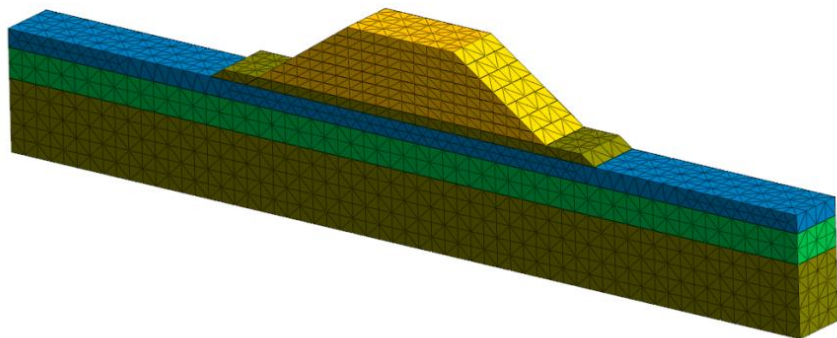
Вариант без усиления основания. Участок дороги Выборг-Каменногорск



Параметры материалов

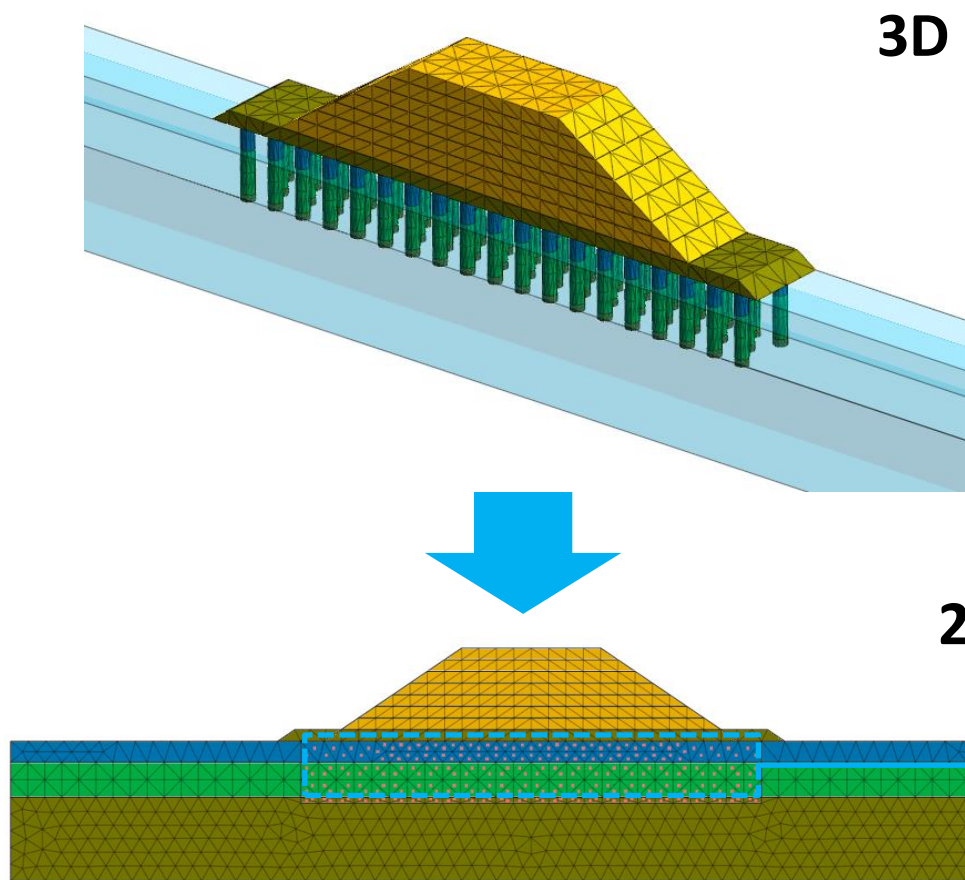
№ИГИ			3-10	3-8	5-5	Материал насыпи	Материал грунтовых свай	Материал гибкого ростверка
Наименование			Суглинки тяжелые пылеватые мягкопластичные	Суглинки тяжелые пылеватые текучие	Гравийный грунт (дресвяный) с песчаным заполнителем, плотный	Песок средней крупности	Щебень	Щебень
Геологический индекс			Ig III	Ig III	g III			
Параметр	Обозначение	Ед. изм						
General (Общие свойства)								
Модель материала	Material model	-	Мора-Кулона	Мора-Кулона	Мора-Кулона	Мора-Кулона	Мора-Кулона	Мора-Кулона
Тип поведения материала	Drainage type	-	Дренированный	Дренированный	Дренированный	Дренированный	Дренированный	Дренированный
Удельный вес грунта выше уровня грунтовых вод	γ_{unsat}	кН/м3	19.4	17.5	21.4	18	19	19
Удельный вес грунта ниже уровня грунтовых вод	γ_{sat}	кН/м3	19.4	17.5	21.4	21	19	19
Parameters (Параметры)								
Модуль Юнга	E'	кН/м2	5 000.0	3 000.0	47 000.0	40 000.0	38 000.0	38 000.0
Коэффициент Пуассона	ν	-	0.35	0.35	0.30	0.30	0.30	0.30
Сцепление	c	кН/м2	12.0	3.0	2.0	2.0	1.0	20.0
Угол внутреннего трения	ϕ	град.	10.0	6.0	41.0	38.0	40.0	40.0

3D



Недостатки:

- Требуется навыков пространственного моделирования,
- Затратный по времени,
- Нет возможности дальнейшей проверки аналитическими методами



3D

2D

Удельное сцепление
Угол внутреннего трения
Модуль деформации



The Design of Vibro Replacement

Heinz J. Priebe

Foundation Pressure 130.00 kN/m²
 Column Distance 1.52 m
 Row Distance 1.32 m
 Grid Area 2.00 m²
 Load Level -1.00 m
 Column Depth 10.00 m
 Considered Depth 20.00 m

Column Material
 Unit Weight 19.00 kN/m³, below 1.60 m Depth 12.00 kN/m³
 Constrained Modulus 100.00 MN/m²
 Friction Angle 40.00 Degree
 Press. Coefficient .22

Subsoil Strata

No.	TopL. [m]	Di. [m]	A/AC	DS [MN/m ²]	DC/DS	gamma [kN/m ³]	my	phi [degree]	c [kN/m ²]
1	-1.00	.00	****	50.00	2.00	19.00	.33	35.00	.00
2	.00	.75	4.53	20.00	5.00	18.00	.33	25.00	5.00
3	.40	.75	4.53	2.00	50.00	16.00	.33	.00	25.00
4	1.00	.75	4.53	1.00	100.00	15.00	.33	.00	20.00
5	1.60	.75	4.53	1.00	100.00	5.00	.33	.00	20.00
6	8.20	.60	7.08	10.00	10.00	7.00	.33	.00	30.00
7	9.00	.60	7.08	20.00	5.00	9.00	.33	30.00	.00
8	10.00	.00	****	20.00	5.00	9.00	.33	30.00	.00
9	20.00	.00	****	20.00	5.00	9.00	.33	30.00	.00

Ground Water Table 1.60 m

Top L. = Top Level of Stratum Concerned
 Dia. = Column Diameter
 A = Grid Area Resp. Reference Area
 AC = Cross-sectional Area of Column
 DC = Constrained Modulus of Backfill
 DS = Constrained Modulus)
 gamma = Unit Weight.)
 my = Poisson's Ratio) of Soil
 phi = Friction Angle)
 c = Cohesion)

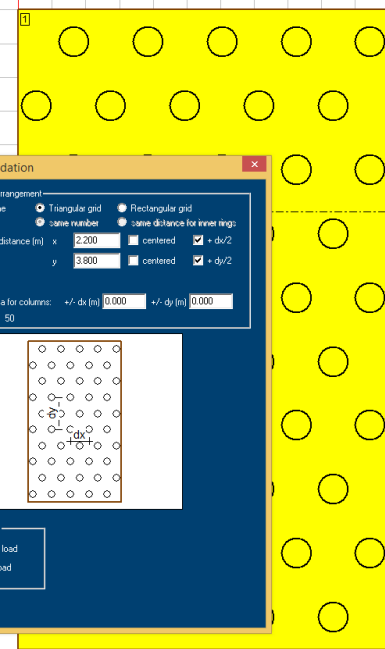
Soil Improvement

No.	n0	d(A/AC)	n1	m1	phi1 [degree]	c1 [kN/m ²]	fd	n2	m2	phi2 [degree]	c2 [kN/m ²]
1											
2	2.34	1.17	2.01	.50	33.16	2.49	****	1.88	.47	33.67	2.64
3	2.34	.09	2.31	.57	25.41	10.94	1.16	2.68	.63	27.73	9.24
4	2.34	.05	2.32	.57	25.54	8.61	1.21	2.82	.65	28.44	7.09
5	2.34	.05	2.32	.57	25.54	8.61	1.27	2.94	.66	28.98	6.80
6	1.78	.52	1.72	.42	19.35	17.45	1.24	2.13	.53	24.04	14.05
7	1.78	1.17	1.65	.40	34.25	.00	****	1.57	.36	33.90	.00
8											

The Proportional Loads on Columns are Approximated to $m = 1 - 1/n$

n0 = Basic Improvement Factor
 d(A/AC) = Addition to the Area Ratio (Column Compressibility)
 n1 = Improvement Factor (with Column Compressibility)
 (→ Recommended for Failure Analyses if $n1 < n2$)
 (when → Overburden by Control Checking)
 fd = Depth Factor (Overburden Constraint)
 n2 = Improvement Factor (Add. with Overburden Constraints)
 m1,2 = Proportional Load on Column)
 phi1,2 = Friction Angle of Compound) Attributable to n1 resp. n2
 c1,2 = Cohesion of Compound)

Settlement	Depth [m]	Infinite Load Area [cm]	w/o Impr. [cm]	Overburden [kN/m ²]
	-1.00	.26	.26	.0
	.00	.14	.26	19.0
	.40	1.37	3.66	26.2
	1.00	2.45	6.90	35.8
	1.60	25.81	75.93	44.8
	8.20	.48	1.03	77.8
	9.00	.41	.65	—
	10.00	6.46	6.46	92.4
		37.37	95.14	—



Foundation

Type: Single footing Strip footing Circular footing Circular ring footing

calculate as infinite

Column arrangement: Triangular grid Rectangular grid

name number name distance for inner rings

Column distance (m) x: 2.200 y: 3.000

centered + dx/2 + dy/2

Add. area for columns: +/- dx (m) 0.000 +/- dy (m) 0.000

Number: 50

Starting coord. (x): 0.000

End coord. (x): 11.000

Starting coord. (y): 0.000

End coord. (y): 19.000

Foundation unit weight (kN/m³): 0.000

Depth of lower edge (m): 0.000

Height (m): 0.000

Slope inclination (deg): 90.000

Load type: dead load live load

Section

Section name: 1 Surface depth for superposition stress: 0.00

Layer no. 1

Name: 3-10

Depth of bottom (m): 1.80

Parameter proposal: Column material

Phi (deg): 10.00

Cohesion c (kN/m²): 12.00

Unit weight gamma (kN/m³): 19.40

Unit w. with buoyancy (kN/m³): 19.40

Young's modulus Es (MN/m²): 5.00

Lateral strain parameter mue (-): 0.35

Column diameter (m): 0.90

Analysis sections (m): 0.50

Buttons: First, Next..., New, Last, Back..., Delete

Buttons: OK, Cancel, Help

Analysis Standard

Analysis standard (only used for the bearing capacity analysis):

DIN 4017:1929 DIN 1054:2005 Eurocode 7 SIA 267 DENORM B 4435-2

with DIN 4017:2005

Free Free Free

Approach for safety factors:

Partial safety factors

Layer par. resistance

Bearing cap. resistance

Actions/Loads

Gamma global

Use load case type: Lc 1/Ac 2/Lc 3

Use load case type Lc 2/3

Safety factors actions/loads: _____

Safety factors resistances: _____

Buttons: OK, Cancel, Help

The Design of vibro replacement

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As an approximation, the compressibility of the column material can be considered in a reduced improvement factor n_1 which results from the formula developed for the improvement factor n_0 when the given reciprocal area ratio A_1/A_0 is increased by an additional amount of $\Delta(A_1/A_0)$.

$$n_1 = 1 + \frac{\Delta_1}{A_1} \left[\frac{1/2 + f(\mu_0, \Delta_1/A_1)}{K_{sc} - f(\mu_0, \Delta_1/A_1)} \right]$$

$$\frac{\Delta_1}{A_1} = \frac{1}{A_1/A_0 - 1} \Delta(A_1/A_0)$$

In using the diagram in Figure 1 this procedure corresponds to such a shifting of the origin coordinates on the abscissa which denotes the area ratio A_1/A_0 ; that the improvement fact to be drawn from the diagram, begins with the ratio of the constrained moduli and not with an infinite value. The additional amount on the area ratio $\Delta(A_1/A_0)$ depending on the ratio constrained moduli D_2/D_3 can be readily taken from the diagram in Figure 2.

4 Consideration of the Overburden

The neglect of the bulk densities of columns and soil means that the initial pressure difference between the columns and the soil which creates bulging depends solely on the distribution foundation load p on the column and soil, and that it is constant all over the column length. matter of fact, to the external loads the weights of the columns W_c and of the soil W_s possibly exceed the external loads considerably, has to be added. Under consideration of additional loads the initial pressure difference decreases asymptotically and the bulging is correspondingly. In other words, with increasing overburden the columns are better supported laterally and therefore, can provide more bearing capacity.

Since the pressure difference is a linear parameter in the derivations of the improvement the ratio of the initial pressure difference and the one depending on depth - expressed as factor $n_0 = f_0 \cdot n_1$ on account of the overburden pressure. For example, at a depth where pressure difference amounts to 50% only of the initial value, the depth factor comes to $f_0 = 0.5$. The depth factor f_0 is calculated on the assumption of a linear decrease of the pressure difference as it results from the pressure lines ($p_0 = \gamma_0 \cdot D$; K_{sc} and $(p_0 + \gamma_0 \cdot d)$ ($K_{sc} = 1$)). However, it has been considered that with decreasing lateral deformations the coefficient of earth pressure from column changes from the active value K_{ac} to the value at rest K_{ar} . Up to the depth which straight line assumed for the pressure difference, meets the actual asymptotic line, the factor lies on the safe side. In practical cases the treatment depth is mostly less. However, considerations advise not to include the advantageous external load on the soil p_0 in the derivation.

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Vibro Replacement is an accepted method for subsoil improvement. Columns of coarse backfill material are installed in the soil by means of the performance of this composite system consisting of stone columns and soil. The performance of this composite system is not determined by simple investigation methods like soundings, and the are not suitable for design purposes. However, theoretically, the effect of Vibro Replacement can be reliably evaluated. The method elaborated on in this paper as described in this contribution, is easy to survey and adaptable to fit the separate consideration of significant parameters. Practically, it can be used for all frequently occurring applications.

1 Introduction

Vibro replacement is part of the deep vibratory compaction technique. Soft soil is improved for building purposes by means of special depth techniques as well as the equipment required is comprehensively described. Contrary to vibro compaction which densifies noncohesive soil by the improves it thereby directly, vibro replacement improves non compact the installation of load bearing columns of well compacted, coarse grained material. The question to what extent the density of compacted soil will be improved, depends not only on the parameters of the soil being dealt with on the procedure adopted and the equipment provided. However, reliable prognosis is balanced by the fact that the improvement achieved by soundings.

With vibro replacement the conditions are more or less reversed. Conclude large-scale load tests can prove the benefit of stone columns. However, can be drawn about the degree of improvement which results from the stone columns only without any densification of the soil being because the essential parameters attributable to the geometry of the material can be determined fairly good. In such a prognosis the proper equipment and the procedure play an indirect role only and that is in the of the column diameter.

Basically, the design method described herewith was developed some

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$$f_0 = \frac{1}{1 + \frac{K_{sc} \cdot W_c / W_s}{K_{sc} \cdot p_c} \cdot \frac{W_c}{p_c}}$$

$$p_c = \frac{p}{\frac{A_c}{A} \cdot \frac{1 - \Delta_1/A_1}{p_c}}$$

$$p_c = \frac{1/2 + f(\mu_0, \Delta_1/A_1)}{K_{sc} - f(\mu_0, \Delta_1/A_1)}$$

$$W_c = \Sigma(\gamma_c \cdot \Delta d), \quad W_s = \Sigma \gamma \cdot D$$

$$K_{sc} = 1 - \sin \varphi_c$$

The simplified diagram in Figure 3 considers the same bulk density γ for columns and soil on the safe side. Therefore for safety reasons, the lower value of the soil γ_s should be in this diagram always.

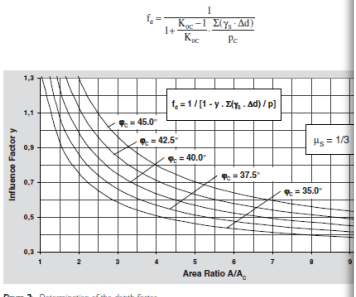


Figure 3 Determination of the depth factor

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It may be emphasized: The design method refers to the improving effect of soil which is otherwise unaltered in comparison to the initial state. In established by which stone columns improve the performance of the composite system is increased respectively settlements are reduced refer to this basic value.

In many practical cases the reinforcing effect of stone columns installed superposed with the densifying effect of vibro compaction, i.e. the installation of the soil between in this case, first of all the densification of the soil and only then - on the basis of soil data adapted correspondingly - the design follows.

Notation

A	grid area	p	area load resp. settlement
b	foundation width	W	weight
c	cohesion	W	weight
d	improvement depth	γ	reduction factor
d _{gr}	depth of ground failure	γ	unit weight
D	improvement depth	γ	safety against
f ₀	depth factor	γ ₀	Poisson's ratio
K	coefficient of earth pressure	σ _v	bearing capacity
m	proportional load on stone columns	φ	friction angle
n	improvement factor		

Used subscripts, dashes and apostrophes follow from the context. Generally, subscripts mean soil. With the exception of K_{sc} as coefficient for earth pressure at rest (K_{sc} = 0 means a basic respectively an initial value).

2 Determination of the Basic Improvement Factor

The fairly complex system of vibro replacement allows a more or less for the well defined case of an unlimited load on an unlimited column cell with the area A_1 is considered consisting of a single column with the attributable surrounding soil.

Furthermore the following idealized conditions are assumed:

- The column is based on a rigid layer
- The column material is incompressible
- The improvement factor n_0 of column and soil is neglected

5 Compatibility Controls

The single steps of the design procedure are not connected mathematically and they contain simplifications and approximations. Therefore, at marginal cases compatibility controls have to be performed which guarantee that no more load is assigned to the columns than they can bear at all in accordance with their compressibility.

At increasing depths, the support by the soil reaches such an extent that the columns do not bulge anymore. However, even then the depth factor will not increase to infinity as results from the assumption of a linearly decreasing pressure difference. Therefore, the first compatibility control limits the depth factor and thereby the load assigned to the columns so that the settlement of the columns resulting from their inherent compressibility does not exceed the settlement of the composite system. In the first place this control applies when the existing soil is considered pretty dense or stiff.

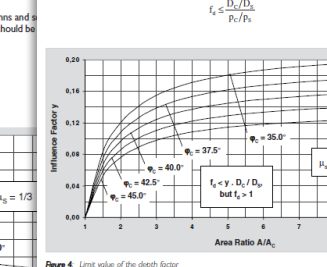


Figure 4 Limit value of the depth factor

The maximum value of the depth factor can be drawn also from the diagram in Figure 4. By the way, a depth factor $f_0 < 1$ should not be considered, even though it may result from the calculation. In this case the second compatibility control is imperatively required which relates to the maximum value of the improvement factor. In a certain way this control resembles the first one. It guarantees that the settlement of the columns resulting from their inherent compressibility does not exceed the settlement of the surrounding soil resulting from its compressibility by the loads which are

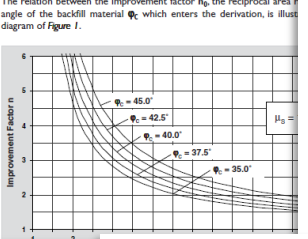
The improvement of a soil achieved at these conditions by the existing soil is evaluated on the assumption that the column material shears from the surrounding soil reacts elastically. Furthermore, the soil is assumed to be the column installation to such an extent that its initial resistance comes to the coefficient of earth pressure amounts to $K = 1$. The result of this as basic improvement factor n_0 .

$$n_0 = 1 + \frac{\Delta_1}{A_1} \left[\frac{1/2 + f(\mu_0, \Delta_1/A_1)}{K_{sc} - f(\mu_0, \Delta_1/A_1)} \right]$$

$$f(\mu_0, \Delta_1/A_1) = \frac{(1 - \mu_0)(1 - \Delta_1/A_1)}{1 - 2\mu_0 + \Delta_1/A_1}$$

$$K_{sc} = \tan^2(45^\circ - \varphi_c/2)$$

A poisson's ratio of $\mu_0 = 1/3$ which is adequate for the state of final soil leads to a simple expression.

$$n_0 = 1 + \frac{\Delta_1}{A_1} \left[\frac{S - \Delta_1/A_1}{4 \cdot K_{sc} - (1 - \Delta_1/A_1)} \right]$$


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assigned to each. In the first place this second control applies when the soil is pretty loose or soft.

$$n_{max} = 1 + \frac{\Delta_1}{A_1} \left(\frac{D_2}{D_3} - 1 \right)$$

It has to be observed that the actual area ratio A_1/A_0 has to be used the modified value A_1'/A_0 . Because of the simple equation, an index n can be calculated.

6 Shear Values of Improved Ground

The shear performance of ground improved by vibro replacement under shear stress rigid elements may break successively, stone has been transferred to neighbouring columns. For example, a bearing capacity of the total group of columns installed has received an increased portion of the total load m thereby will and the improvement factor n .

$$m = (n - 1) + A_c/A_0$$

Simplifying the recommended design procedure does not consider surrounding soil caused by the bulging of the columns. Therefore, the soil receive a greater portion of the total load than overestimate the shear resistance of the columns when averaged on columns and soil, the proportional load on the columns approximation seems to be adequate:

$$m' = (n - 1)/n$$

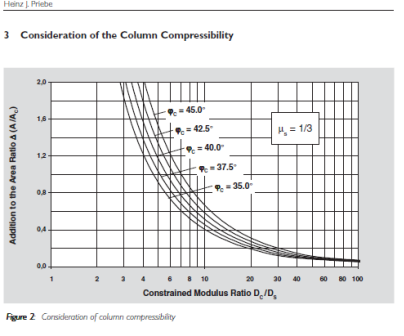
The diagram in Figure 5 shows in solid lines the proportion dashed lines the not reduced one m .

According to the proportional loads on columns and soil, the composite system can be readily averaged.

$$\tan \varphi = m' \tan \varphi_c + (1 - m') \tan \varphi_s$$

Since in most practical cases possible lines of sliding circle survey it is recommended to consider the depth factor in design usually with a load portion of the stone columns m_1 related to the increased factor $n_1 = f_0 \cdot n_1$.

The cohesion of the composite system depends on the proportion $c = (1 - \Delta_1/A_1) \cdot c_0$



The compacted backfill material of the columns is still compressible. Therefore, any load causes settlements which are not connected with bulging of the columns. Accordingly in the case of soil replacement where the area ratio amounts to $A_1/A_0 = 1$, the actual improvement factor does not achieve an infinite value as determined theoretically for non compressible material, but it coincides at best with the ratio of the constrained moduli of column material and soil. In case for compacted backfill material as well as for soil a constrained modulus is meant as found by large scale oedometer tests. Unfortunately, in many cases soundings are carried out within the columns and wrong conclusions about the modulus are drawn from the results which are sometimes very moderate only.

It is relatively easy to determine at which area ratio of column cross section and grid size (A_1/A_0), the improvement factor n_0 corresponds to the ratio of the constrained moduli of columns and soil D_2/D_3 . For example, at $\mu_0 = 1/3$ the lower positive result of the following expression (with $n_0 = D_2/D_3$) delivers the area ratio (A_1/A_0), concerned.

$$\left(\frac{A_1}{A_0} \right) = \frac{4 \cdot K_{sc} \cdot (n_0 - 2) + 5}{2 \cdot (4 \cdot K_{sc} - 1)} + \frac{1}{2} \sqrt{\frac{4 \cdot K_{sc} \cdot (n_0 - 2) + 5}{4 \cdot K_{sc} - 1} + \frac{16 \cdot K_{sc} \cdot (n_0 - 1)}{4 \cdot K_{sc} - 1}}$$

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The installation of stone columns possibly creates damages to the soil structure which are difficult to survey. For safety reasons, it seems to be advisable to consider the cohesion also proportional to the loads, i.e. pretty low, although this is proportional to not based on soil mechanical aspects.

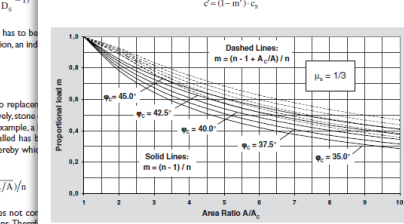


Figure 5 Proportional load on stone columns

7 Settlement of Single and Strip Footings

It is not (yet) possible to determine directly the performance of single or strip footings on vibro improved ground. The design assumes on the performance of an unlimited column grid below an unlimited load area. The total settlements s_c , which results for the case at homogeneous conditions, is readily to determine on the basis of the foregoing description with n_0 as an average value over the depth d .

$$s_c = p \cdot \frac{d}{D_2 \cdot n_1}$$

Diagrams which are given in Figure 6 and Figure 7 allow to conclude from this value the settlements of single or strip footings on groups of columns. These diagrams - with the diameter of the stone columns D as a parameter - are based on numerous calculations which considered load distribution on one side and a lower bearing capacity of the outer columns of the column group below the footing on the other side.

Прочностные характеристики усиленного массива. DC-Vibro

№ ИГЭ	Наименование	Характеристики природного грунта		Характеристики усиленного грунта. Шаг 2.6x2.2				Характеристики усиленного грунта. Шаг 2.2x1.9			
		Удельное сцепление, кПа	Угол внутреннего трения, град	Удельное сцепление, кПа		Угол внутреннего трения, град		Удельное сцепление, кПа		Угол внутреннего трения, град	
3-10	Суглинки тяжелые пылеватые мягкопластичные	12.0	10.0	7.67	-36.1%	22.57	+125.7%	6.67	-44.4%	25.2	+152%
3-8	Суглинки тяжелые пылеватые текучие	3.0	6.0	1.91	-36.3%	20.42	+240.3%	1.65	-45%	23.48	+291.3%
5-5	Гравийный грунт (дресвяный) с песчаным заполнителем, плотный	2.0	41.0	1.43	-28.5%	40.72	-0.68%	1.34	-33%	40.67	-0.8%

Упрощенная методика определения характеристик усиленного массива, основанная на методе Priebe

$$n = 1 + \frac{A_c}{A} \cdot \left[\frac{5 - A_c / A}{4K_{ac} \cdot (1 - A_c / A)} - 1 \right] \quad (1) \quad K_{ac} = \tan^2(45^\circ - \varphi_c / 2) \quad (3) \quad c' = (1 - m') \cdot c_s \quad (5)$$

$$m' = (n - 1) / n \quad (2) \quad \tan \bar{\varphi} = m' \cdot \tan \varphi_c + (1 - m') \tan \varphi_s \quad (4)$$

φ_s - угол внутреннего трения грунта

φ_c - угол внутреннего трения материала щебеночных свай

m' - пропорциональный параметр, определяемый по формуле (2)

n – коэффициент усиления, который рассчитывается в зависимости от отношения площадей щебеночных свай и усиленного массива и определяемый по формуле (1)

A_c - площадь щебеночной сваи,

A_s - площадь влияния щебеночной сваи,

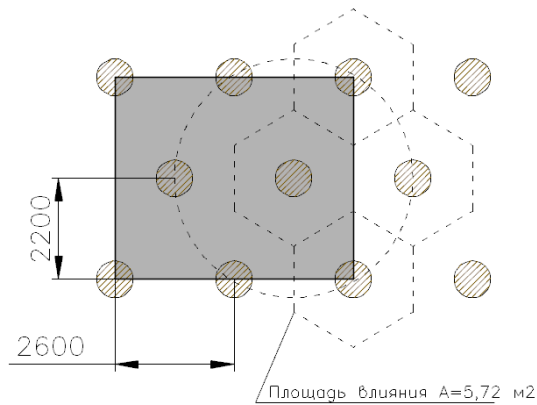
K_{ac} - коэффициент активного давления материала щебеночных свай, определяемый по формуле (3)

c_s - удельное сцепление грунта

\bar{c} - удельное сцепление усиленного массива

Сравнение результатов расчета в программе DC-Vibro и упрощенным методом

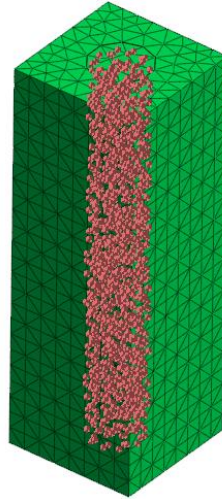
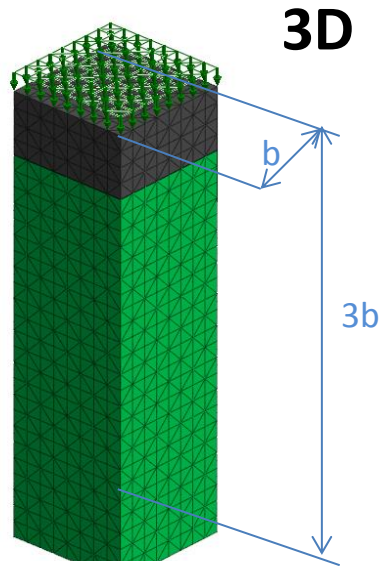
№ ИГЭ	Наименование	Характеристики природного грунта		Характеристики усиленного грунта. Шаг 2.6x2.2						Характеристики усиленного грунта. Шаг 2.2x1.9					
		Удельное сцепление, кПа	Угол внутреннего трения, град	Удельное сцепление, кПа			Угол внутреннего трения, град			Удельное сцепление, кПа			Угол внутреннего трения, град		
				DC-Vibro	Упрощенный метод	Соотношение	DC-Vibro	Упрощенный метод	Соотношение	DC-Vibro	Упрощенный метод	Соотношение	DC-Vibro	Упрощенный метод	Соотношение
3-10	Суглинки тяжелые пылеватые мягкопластичные	12.0	10.0	7.7	7.5	-1.7%	22.6	22.9	+1.5%	6.7	6.5	-2.6%	25.2	25.7	+1.8%
3-8	Суглинки тяжелые пылеватые текучие	3.0	6.0	1.9	1.9	-1.3%	20.4	20.7	+1.4%	1.7	1.6	-1.6%	23.5	23.8	+1.5%
5-5	Гравийный грунт (дресвяный) с песчаным заполнителем, плотный	2.0	41.0	1.4	1.3	-12.1%	40.7	40.6	-0.22%	1.3	1.1	-19.2%	40.7	40.5	-0.3%



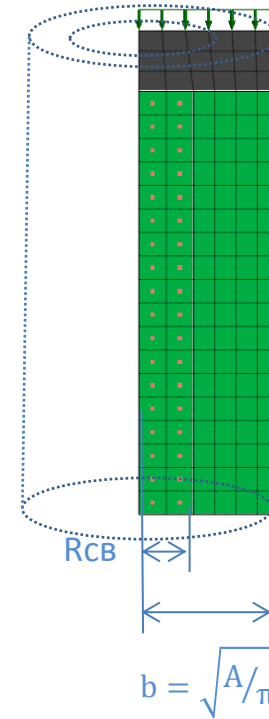
$$E_{oed} = \frac{\Delta p}{\Delta \varepsilon}$$

$$E' = E_{oed} \times \beta$$

$$\beta = 1 - \frac{2\nu^2}{1 - \nu}$$



2D, Axisymmetric



Сравнение результатов определения модуля деформации в плоской и пространственной постановке

		Результаты определения одометрического модуля деформации E _{oed} , кН/м ²					
		Шаг свай усиления 2.6x2.2			Шаг свай усиления 2.6x2.2		
№ИГЭ	Наименование	3D	2D	%	3D	2D	%
3-10	Суглинки тяжелые пылеватые мягкопластичные	11 675.68	11 428.57	2.1%	13 432.84	13 043.48	2.9%
3-8	Суглинки тяжелые пылеватые текучие	7 474.05	7 272.73	2.7%	9 137.06	8 750.00	4.2%
5-5	Гравийный грунт (дресвяный) с песчаным заполнителем, плотный	61 891.12	61 855.67	0.1%	61 224.49	61 403.51	-0.3%

По результатам проведения испытаний численным методом, значения одометрического модуля в плоской осесимметричной постановке **2D** от **2,1% до 4,2% менее** полученных в пространственной постановке

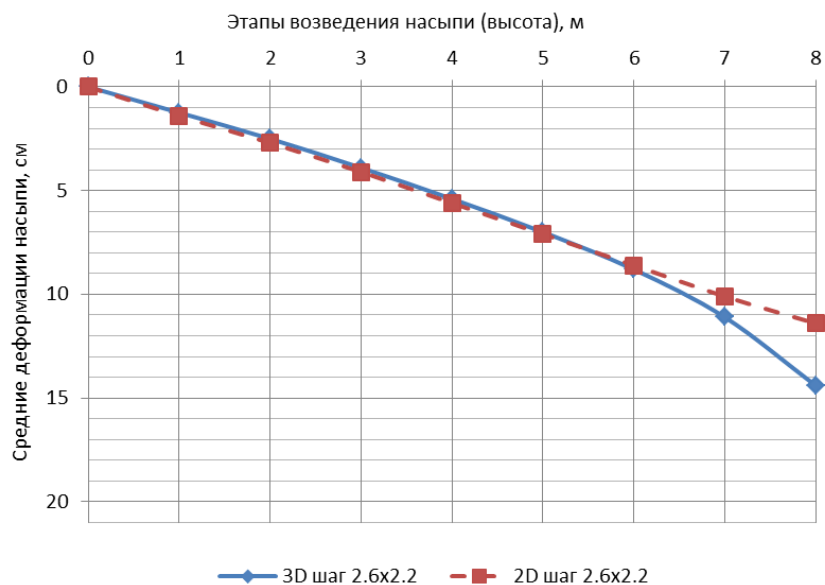
Параметры усиленного грунта

№ ИГЭ	Наименование	Характеристики природного грунта			Характеристики усиленного грунта. Шаг 2.6x2.2						Характеристики усиленного грунта. Шаг 2.2x1.9					
		Удельное сцепление, кПа	Угол внутреннего трения, град	Модуль деформации	Удельное сцепление, кПа		Угол внутреннего трения, град		Модуль деформации		Удельное сцепление, кПа		Угол внутреннего трения, град		Модуль деформации	
3-10	Суглинки тяжелые пылеватые мягкопластичные	12.0	10.0	5 000.0	7.7	-36%	22.6	126%	8 491.4	70%	6.7	-44%	25.2	152%	9 691.3	94%
3-8	Суглинки тяжелые пылеватые текучие	3.0	6.0	3 000.0	1.9	-36%	20.4	240%	5 403.6	80%	1.7	-45%	23.5	291%	6 501.3	117%
5-5	Гравийный грунт (дресвяный) с песчаным заполнителем, плотный	2.0	41.0	47 000.0	1.4	-29%	40.7	-1%	38 536.1	-18%	1.3	-33%	40.7	-1%	38 254.4	-19%

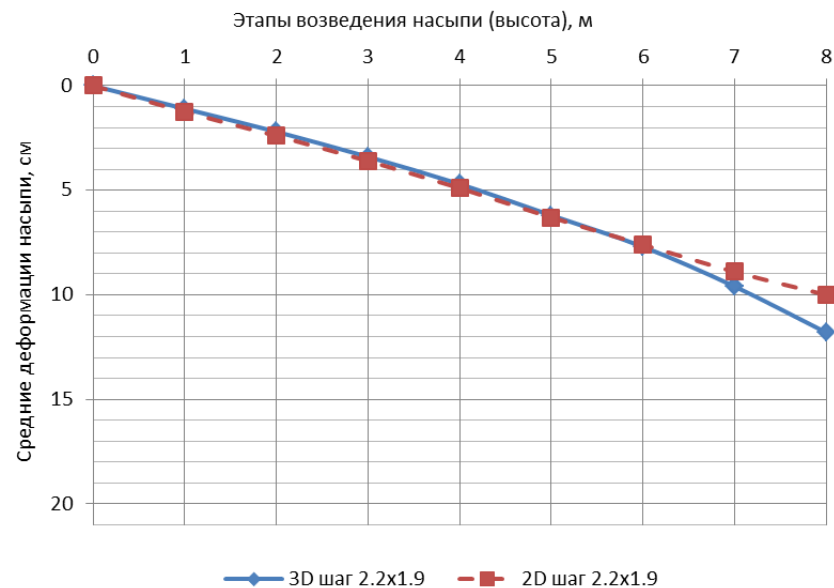
По результатам расчетов,

- Удельное сцепление усиленного массива **уменьшилось**,
- Угол внутреннего трения **увеличился** от **126 %** до **291 %**
- Модуль деформации **увеличился** от **70%** до **117%**

Шаг 2.6x2.2



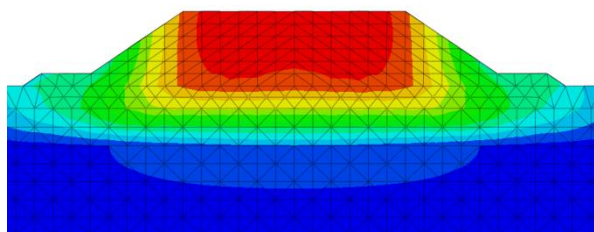
Шаг 2.2x1.9



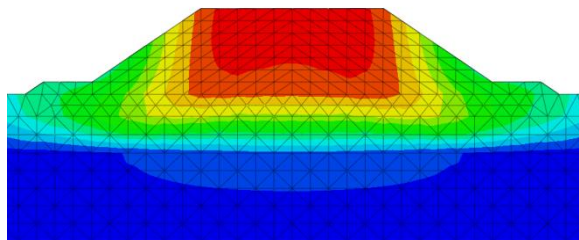
Графические результаты расчета при шаге 2,2x1,9 м

3D

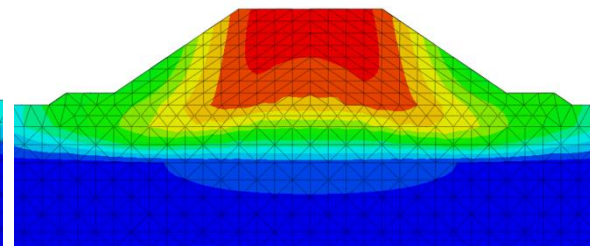
Насыпь 6 м



Насыпь 7 м

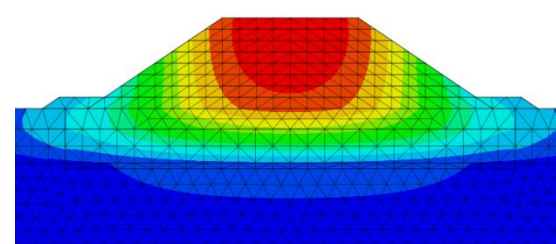
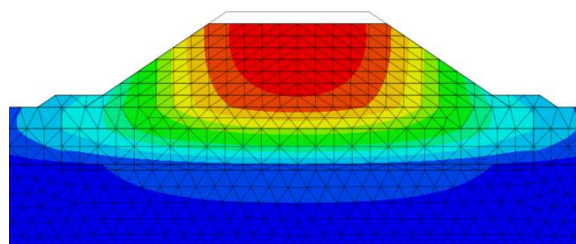
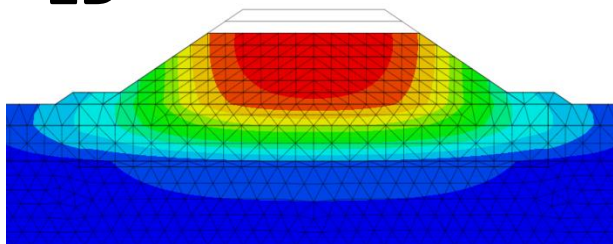


Насыпь 8 м



Куст = 1,109

2D



1. Представленная в презентации упрощенная методика определения прочностных характеристик усиленного массива позволяет определить характеристики с точностью $\pm 3\%$ в сравнении с оригинальной аналитической методикой
2. **Определение модуля деформации** усиленного массива методом конечных элементов **ВОЗМОЖНО в плоской постановке с осесимметричными граничными условиями**. Разница в полученных результатах 3D и 2D составила от **2,1% до 4,2%**
3. При использовании представленных рекомендаций:
Разница между пространственным и плоским решениям **в пределах линейной зависимости деформаций не превышает 10%**, при определении деформаций
4. **При расчете насыпей высотой более 6 м** на слабом основании при усилении основания грунтовыми сваями, **рекомендуется** выполнять расчеты **в пространственной постановке**

