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7 **Discussion: Horizontal stress increase induced by deep vibratory** 8 **compaction**

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31 32 **Contribution by L. Bałachowski, N. Kurek and J. Konkol**

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34 Evaluation of the horizontal stress increase induced by deep compaction is one of the most
35 difficult topics in geotechnics. The approach of Massarsch et al. (2020) to determine the
36 overconsolidation ratio (OCR) in compacted soil based on sleeve friction and lateral stress
37 index seems to be questionable. In Figures 12 and 24 of their paper, the irregular shape of the
38 OCR with depth and sharp peaks cannot be physically explained. Moreover, the OCR values
39 based on sleeve friction and lateral stress index are inconsistent. For instance, 14 days after
40 dynamic compaction, the OCR values determined with the lateral stress index(Figure 9) are
41 four to seven times higher than those based on sleeve friction (Figure 7). Even greater
42 inconsistency in the OCR values determined using cone penetration test (CPT) with water
43 pressure measurement (CPTU) and the Marchetti dilatometer test (DMT) was shown for
44 vibroflotation (Figures 12 and 14). Very high OCR values, largely exceeding 100 (Figure 14),
45 estimated with the correlation using the DMT are highly unrealistic. The upper bound of the
46 OCR-based K_0 should correspond to the passive earth pressure coefficient. Additionally, the
47 use of sleeve friction is generally considered less reliable than the cone resistance, so the
48 proposed correlation (Equation 2) should be used with caution. In the contributors' opinion, it
49 would be better to use the OCR correlations based on combined CPTU and DMT tests, as
50 proposed by Baldi et al. (1986), Monaco et al. (2014) or Marchetti (2015). Additionally,

51 Figure 17 seems to be erroneous, as the report of sleeve friction elaborated using the data
52 from Figure 15 is higher than one at larger depths.

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54 To estimate the OCR of compacted sand, the authors used Equation 12 based on calibration
55 chamber tests with the soil mass prepared by pluviation and then mechanically overloaded
56 (Lee et al., 2011). Such a procedure is, however, quite different to the mechanisms of deep
57 soil vibratory compaction with rearrangement of grains, prestressing and, finally, the
58 formation of a new soil fabric. To meet field conditions, such a type of correlation should be
59 critically reviewed, including the results of calibration chamber tests where the soil mass was
60 densified with a vibrator.

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62 The authors used the classification of Robertson et al. (1986) to present the evolution of soil
63 behaviour type due to the compaction process. In the contributors' opinion, use of the diagram
64 presented by Robertson (1990) or its updated version (Robertson, 2009) would be more
65 appropriate as it allows one to distinguish between normally consolidated and
66 overconsolidated soils. After vibratory compaction in Gdynia, the soil is classified as
67 normally consolidated according to the chart of Robertson (1990) (Figure 33), which is
68 consistent with a mechanism of vibroflotation where only lateral stress increases. After
69 dynamic compaction in Gdańsk, however, the soil is classified as overconsolidated (Figure
70 34). Such soil type behaviour reflects, in the contributors' opinion, the mechanism of dynamic
71 compaction, where the soil is subjected to dynamic contact vertical stress induced by the
72 pounder impact, as estimated by Jessberger and Beine (1981) and Mayne and Jones (1983).

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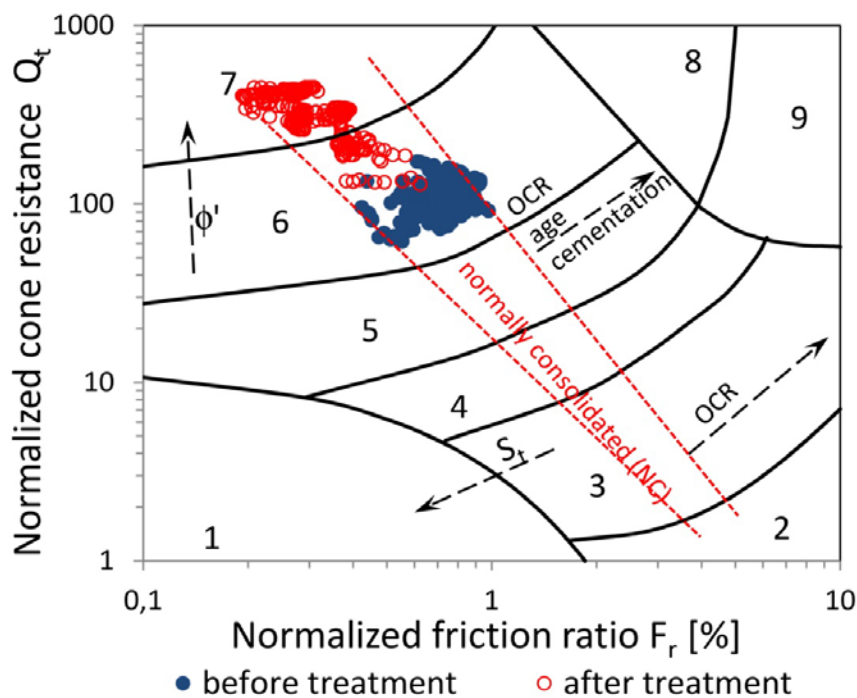
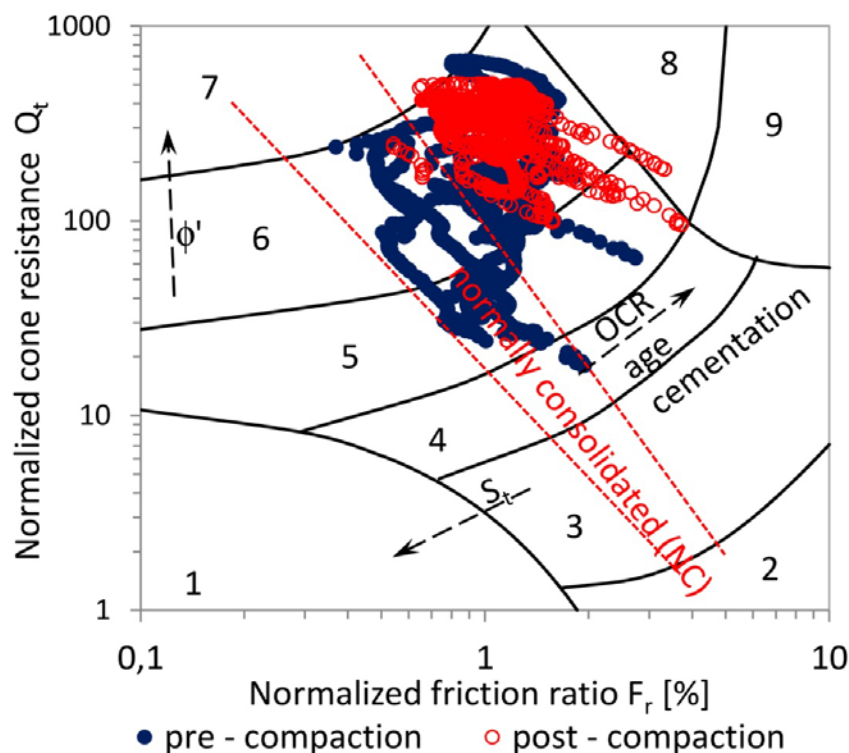


Figure 33. Robertson 1990 chart for soil treated by vibroflotation, Gdynia, Poland, Bałachowski and Kurek (2015). ϕ' , angle of internal friction; S_t , sensitivity



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Figure 34. Robertson 1990 chart for soil treated by dynamic compaction, Gdańsk, Poland, Kurek and Bałachowski (2015)

87 Authors' reply

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1. Introduction

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In the paper under discussion (Massarsch et al., 2020) five case histories were investigated, which all showed that the sleeve resistance, f_s (CPT), and horizontal stress index, K_D (DMT), increased independently of the compaction method. The paper demonstrates that permanent changes in horizontal stress do occur as a result of deep vibratory compaction. An important aspect of the proposed approach is that, when assessing preloading, data interpretation should be based on changes of soil parameters rather than on single values after the completed compaction effort. The critique offered by the contributors can be summarised in the following three points.

- 100 (a) Changes in sleeve resistance (CPT) or horizontal stress index (DMT) do not reflect
- 101 changes in horizontal effective stress.
- 102 (b) The strong variation of the OCR shows that the authors' proposed horizontal stress
- 103 concept is incorrect.
- 104 (c) An increase in horizontal effective stress cannot be related to a preloading
- 105 ('overconsolidation') effect.
- 106

107 In the authors' opinion, these three points are based on conjecture rather than factual evidence
108 and do not address the fundamental and widely accepted concepts presented in the paper.

109 Rather, they focus on the fact that the interpretation of field data, in some cases, produces a
110 large scatter.

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112 **2. Questionable quality of geotechnical data**

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114 Two of the contributors were co-authors of two of the case histories (Gdańsk and Gdynia)
115 cited in the original paper. The case history presented by Kurek and Bałachowski (2015)
116 (CPTU/DMT control of heavy tamping compaction of sands) describes the application of
117 dynamic compaction (heavy tamping) to treat loose to medium dense sand layers and states
118 that ‘the cone penetration test CPTU and the dilatometer test DMT were used as main tools of
119 compaction control’ (Kurek and Bałachowski, 2015, 2015: p. 2). The case history presented
120 by Bałachowski and Kurek (2015) (Vibroflotation control of sandy soils using DMT and
121 CPTU) describes the application of vibroflotation. However, although the titles of both case
122 histories mention CPTU, the papers omit pore water pressure measurements. Also, the depths
123 to groundwater tables are missing. While CPTU and DMT investigations were carried out at
124 three locations prior to compaction and after compaction, respectively, only the results of one
125 CPT and one DMT before and after treatment are reported. The absence of these
126 measurements may be the cause of the scatter of the OCR values derived from the Gdańsk
127 and Gdynia case histories.

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129 In addition, in the paper by Bałachowski and Kurek (2015) only reports test data for one CPT
130 without pore pressure measurement and one DMT. Vibroflotation causes strong lateral
131 vibrations and the ensuing increase of horizontal stress is evident from the strong increase in
132 K_D measurements. It would be unreasonable to accept that f_s would decrease while K_D would
133 increase. Therefore, the authors’ interpretation is that the f_s data are erroneous and that f_s
134 actually increased, similar to K_D .

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136 When interpreting geotechnical data from the case histories, the authors did not comment on
137 the accuracy of the reported data. Despite our concern regarding the quality of the two case
138 histories mentioned, due to the large amount of other data from other cited cases, the authors’
139 general conclusion was that horizontal stresses increased in all the case histories, independent
140 of the compaction method. In the following, the points raised by the contributors will be
141 addressed in the order made. The text from the discussion is quoted, followed by the authors’
142 response.

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144 **3. Response to specific comments**

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- 146 ■ The approach of Massarsch et al. (2020) to determine the OCR in compacted soil
147 based on sleeve friction and lateral stress index seems to be questionable.

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149 The generalised statement ‘seems to be questionable’ is rejected because no factual
150 information is given as a base to the statement. The paper addresses changes in horizontal
151 stress due to vibratory compaction. In the authors’ opinion, and substantiated by a large
152 number of case histories, both sleeve resistance f_s and horizontal stress index K_D are sensitive
153 to changes in horizontal stress and changes measured between before and after compaction do
154 reflect the preloading effect.

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- 156 ■ In Figures 12 and 24 ... the irregular shape of the OCR with depth and sharp peaks
157 cannot be physically explained. Moreover, the OCR values based on sleeve friction
158 and lateral stress index are inconsistent.

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The objective of the paper was not to determine the OCR, but to address horizontal stress increase as measured by CPTs and DMTs. The reason for the variation of OCR in Figures 12 and 24 is due to the fact that, after compaction by vibroflotation, f_s is reported to have decreased significantly while K_D increased by a factor of 10 – 15. The authors' conclusion is that the accuracy of both the CPT and DMT measurements of the particular case history (Kurek and Bałachowski, 2015) is questionable, which therefore caused a considerable scatter in the evaluation using the cited records.

- For instance, 14 days after dynamic compaction, the OCR values determined with the lateral stress index (Figure 9) are four to seven times higher than those based on sleeve friction (Figure 7).

Compaction was carried out in granular soil with a low fines content. CPT data (cone resistance q_c and sleeve resistance f_s) show a marked increase 1 day after compaction and only a small increase during the following period. However, the reported DMT (K_D) measurements show only a slight increase after 1 day, but a strong increase during the following 13 days.

- Even greater inconsistency in the OCR values determined using CPTU and DMT was shown for vibroflotation (Figures 12 and 14).

As already stated, the sleeve resistance measurements after compaction in the cited case history are questionable (Bałachowski and Kurek, 2015). The contributors stated that 'granular material supply was used from the surface' but did not provide information regarding the added soil volume (Bałachowski and Kurek, 2015: p. 1). It is unreasonable that the friction ratio R_f would decrease by more than 50%.

- The upper bound of the OCR-based K_0 should correspond to the passive earth pressure coefficient.

Rather than using the OCR, the authors applied the preloading stress margin (the margin between preloading stress and vertical effective stress). This was because the margin is, in effect, the relatively small difference between two larger numbers, which results in uncertainty of the OCR. Moreover, the reported OCR values also reflect the uncertainty (inaccuracy) of the cited geotechnical information.

- Additionally, the use of sleeve friction is generally considered less reliable than the cone resistance, so the proposed correlation (Equation 2) should be used with caution.

The authors agree that sleeve resistance is more prone to variations than cone resistance. However, in the authors' opinion, changes in f_s reflect changes in horizontal stress better than q_c . While the accuracy of the absolute value of f_s can be low, the ratio of sleeve resistance (the ratio of sleeve resistance determined after compaction to that before compaction) is significantly more reliable.

- In the contributors' opinion, it would be better to use the OCR correlations based on combined CPTU and DMT tests, as proposed by Baldi et al. (1986), Monaco et al. (2014) or Marchetti (2015).



209 The use of a combination of CPT and DMT results is potentially useful for determining the
210 stress history of soil deposits. However, in the case of soil compaction, the authors prefer to
211 use changes in horizontal stress based on f_s and K_D separately. In the case of soil compaction,
212 the conservative approach is to assume that, prior to treatment, the soil deposit was normally
213 consolidated.

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- 215 ■ Additionally, Figure 17 seems to be erroneous, as the report of sleeve friction
216 elaborated using the data from Figure 15 is higher than one at larger depths.

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218 Figure 17 is correct. As stated in the paper under discussion

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220 *... the sleeve resistance down to 5 m depth was unrealistically low and was neglected.*
221 *Therefore, the pre-compaction sleeve resistance was not used to determine the increase in*
222 *horizontal stress, as it would give unacceptably high improvement values.*

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- 224 ■ To estimate the OCR of compacted sand the authors used Equation 12 based on
225 calibration chamber tests with the soil mass prepared by pluviation and then
226 mechanically overloaded (Lee et al., 2011). Such a procedure is, however, quite
227 different to the mechanisms of deep soil vibratory compaction with rearrangement of
228 grains, prestressing and, finally, the formation of a new soil fabric.

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230 The sample preparation method was described in detail by Choi et al. (2010). Pluviation is a
231 dynamic deposition process that is particularly intense when trying to achieve a density index
232 (relative density) exceeding about 60%. After pluviation, the sample was subjected to one
233 static preloading cycle. If the sample had been subjected to several loading and unloading
234 cycles, as suggested by the contributors, the preloading effect would have been even more
235 pronounced. Therefore, the authors' cited data (Lee et al., 2011) actually underestimate the
236 effect of the preloading.

237

238 During vibratory compaction, a soil deposit is subjected to cyclic loading and unloading with
239 a large number of loading cycles. As stated by Rowe (1954), compaction could be interpreted
240 as the repeated application and removal of a static surcharge. Rowe suggested that virtually all
241 peak soil stresses induced by surcharge loading would be retained after surcharge removal.
242 Based on the concept of cyclic loading during vibratory compaction, Duncan and Seed (1986)
243 and Symons and Clayton (1992) developed semi-empirical procedures for estimating
244 horizontal stresses due to vibratory compaction. Rearrangement, in the sense of relative
245 motion between soil particles, occurs in a similar manner for compaction and preloading.
246 These considerations also apply to deep compaction of granular soils, a fact that needs to be
247 recognised, as stated by Massarsch and Fellenius (2002).

248

- 249 ■ ... use of the diagram presented by Robertson (1990) or its updated version
250 (Robertson, 2009) would be more appropriate as it allows one to distinguish between
251 normally consolidated and overconsolidated soils. After vibratory compaction in
252 Gdynia, the soil is classified as normally consolidated according to the chart of
253 Robertson (1990) (Figure 33), which is consistent with a mechanism of vibroflotation
254 where only lateral stress increases. After dynamic compaction in Gdańsk, however,
255 the soil is classified as overconsolidated (Figure 34).

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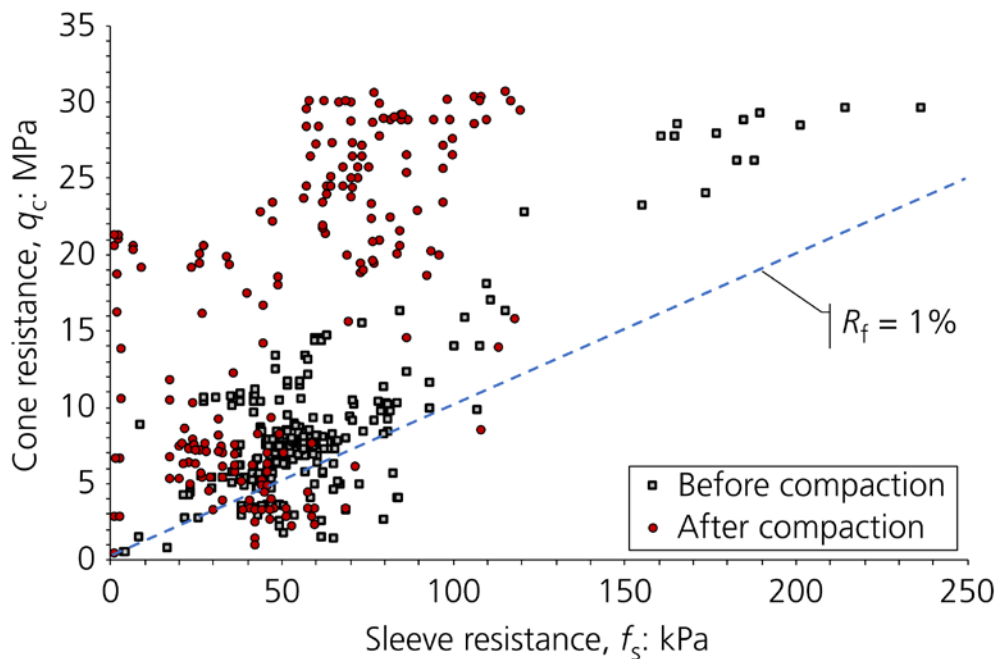
257 The reliability of soil behaviour type (SBT) charts depends on the accuracy of sleeve
258 resistance measurements. However, soil compaction significantly changes horizontal stresses



259 and thus sleeve resistance, which is demonstrated by the case histories presented in the paper
260 under discussion. Normalised SBT charts apply absolute values of cone resistance and sleeve
261 resistance, which disguises the effect of the rearrangement of the soil fabric, easily leading to
262 erroneous conclusions (e.g. the soil type would have changed as a result of compaction).

263
264 Vibroflotation Gdynia: according to the normalised SBT chart provided by the contributors
265 (Figure 33), the soil category changed, but the soil deposit remained normally consolidated.
266 However, this conclusion is, in the authors' opinion, due to inaccurate sleeve resistance
267 measurements. This effect is illustrated in Figure 35, where the same data are plotted in a non-
268 normalised diagram, as suggested by Massarsch and Fellenius (2002).

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273 **Figure 35.** Linear chart of cone resistance against sleeve resistance. Evaluation of soil treated
274 by vibroflotation, Gdynia Poland (Bałachowski and Kurek, 2015). For ease of evaluation, the
275 friction ratio $R_f = 1\%$ is indicated

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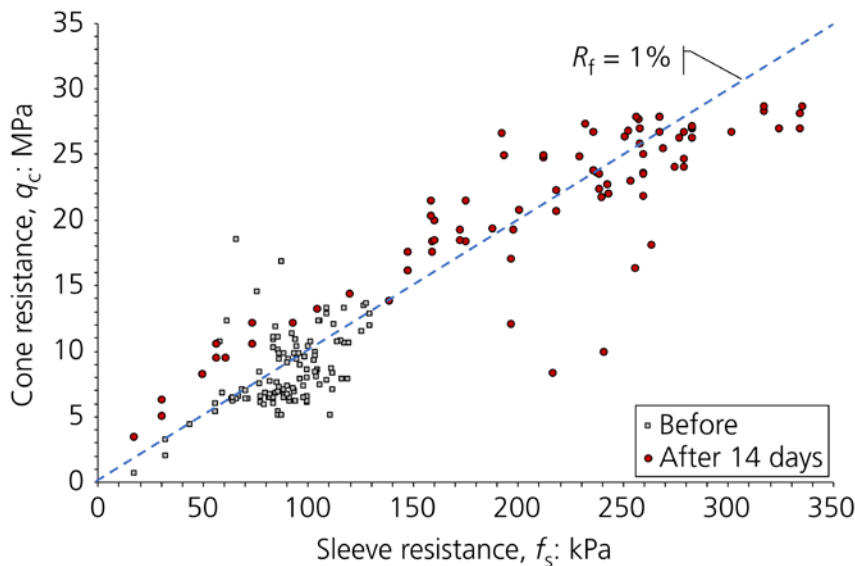
277 The authors agree with the contributors that horizontal stresses increase as a result of
278 vibroflotation. Therefore, it is difficult to follow their assertion, that f_s – which is sensitive to
279 horizontal stress changes (as is K_D) – would decrease by more than 50%. From Figure 35, it
280 would appear that f_s would decrease in the denser soil layers. This conjecture is contrary to
281 extensive experience published in the literature. For instance, Howie et al. (2000) analysed the
282 effect of vibro-replacement in a sandy soil, similar to the method described by the
283 contributors. Different types of in situ tests were used to evaluate the compaction effect.
284 Testing comprised seismic CPTs, full displacement pressuremeter tests and resistivity CPTs.
285 The CPT data showed that, after treatment, both the cone resistance and the sleeve resistance
286 increased markedly. Howie et al. (2000) concluded

287

288 *After ground treatment, changes were observed in tip resistance, pore pressure response,*
289 *shear wave velocity, the characteristics of pressuremeter curves and bulk resistivity. Some of*
290 *these changes can be caused by changes in lateral stress as well as by density increases.*

291
 292 Dynamic compaction, Gdańsk: the results from the Gdańsk case history where dynamic
 293 compaction was used are replotted in a linear chart of cone resistance against sleeve resistance
 294 in Figure 36. Figure 36 clearly shows the effect of the soil treatment. The soil type (friction
 295 ratio) remained approximately unchanged. However, q_c and f_s increased by approximately by
 296 the same degree. It is obvious from the concepts outlined in the original paper that the treated
 297 soil deposit had become preloaded. The contributors are referred to publications that discuss
 298 the limitation of using SBT charts in connection with vibratory compaction (e.g. Asalemi,
 299 2006; Howie et al., 2000; Nguyen et al., 2014). Nguyen et al. (2014: p. 1120) studied the
 300 effect of vibratory compaction (vibroflotation with the addition of granular material from the
 301 ground surface) on the interpretation of SBT charts, when used for liquefaction evaluation.
 302 They showed that, after treatment, the in situ horizontal effective stresses were significantly
 303 increased. They concluded the following.

304
 305 *The NCEER 1997 CPT-based liquefaction analysis uses the CPT Soil Behavior Type Index,*
 306 *I_c , to infer grain characteristics, such as fines content and plasticity of fines. However, after*
 307 *vibratory ground improvement, the in situ horizontal effective stresses are typically increased*
 308 *(i.e. higher K_0) and are no longer linked to vertical effective stress in the same manner as the*
 309 *case histories. This change in K_0 has an influence on the CPT results and can result in a*
 310 *reduction of the measured I_c value, and a corresponding decrease of apparent fines content.*
 311 *However, it is impossible for the vibratory compaction process to produce a decrease in fines*
 312 *content. The authors have performed extensive CPT, SPT, and soil sampling during recent*
 313 *vibro-replacement (stone column) projects in southern California. The I_c values and fine*
 314 *contents of the soil were compared before and after ground improvement. The authors*
 315 *propose a correction method in order to compensate for the shift in I_c and to maintain the*
 316 *same fines content in the pre- and the post-treatment CPT based liquefaction analyses.*
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 319
 320 **Figure 36.** Linear chart of cone resistance against sleeve resistance. Evaluation of soil treated
 321 by dynamic compaction, Gdańsk, Poland (Kurek and Bałachowski, 2015). For ease of
 322 evaluation the friction ratio $R_f = 1\%$ is indicated
 323

324 ▪ Such soil type behaviour reflects, in the contributors' opinion, the mechanism of
325 dynamic compaction, where the soil is subjected to dynamic contact vertical stress
326 induced by the pounder impact, as estimated by Jessberger and Beine (1981) and
327 Mayne and Jones (1983). The statement is based on conjecture rather than scientific
328 evidence. As demonstrated in the original paper, showing stress changes as a result of
329 different soil compaction methods, all types of vibratory compaction cause a
330 permanent increase in horizontal stress. For a more detailed description of the
331 vibratory compaction process and thereby induced stress changes, reference is made
332 to, for instance, Duncan and Seed (1986), who state The compaction of soil represents
333 a process of load application and removal which can result in significant increases in
334 residual lateral earth pressure. Several theories and analytical methods have been
335 proposed to explain and/or analyse the residual lateral earth pressures induced by soil
336 compaction. Common to all of these is the idea that compaction represents a form of
337 overconsolidation wherein stresses resulting from a temporary or transient loading
338 condition are retained to some extent following removal of this peak load.

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