**Proceedings of the XVII ECSMGE-2019**
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0547

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

# Deep dynamic compaction with falling weight in Norway - Experience and recommendations for application

## Compactage dynamique en profondeur à l'aide d'une masse en chute libre – Retour d'expérience et recommandations de mise en œuvre en Norvège

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**ABSTRACT:** Deep Dynamic Compaction (DDC) with falling weight is a traditional and common compaction technique in Norway. DDC has several areas of application and is often used to compact new constructed rock fills in the sea for industrial projects with conventional shallow. Multiconsult has over 40 years of experience within ground improvement by use of DDC. Kollsnes Gas Processing Plant and Equinor Mongstad Oil Refinery are among the essential industry projects where Multiconsult has been involved over the last four decades. These projects are characterized by very restricted settlement criteria and a high demand on documentation.

The first part of this paper will present theoretical principles and design philosophies for DDC. The second part of this paper will present the experience Multiconsult has obtained within the last 40 years from a practical point of view. Recommended practice, expected settlement and vibrations during compaction and experience within ground improvement regarding strength and stiffness properties will be highlighted from project specific data. In addition, the equipment which may be expected from a Norwegian contractor will be presented as well.

**RÉSUMÉ:** Le compactage dynamique en profondeur à l'aide d'une masse tombant en chute libre est une méthode éprouvée en Norvège. Cette méthode a différentes applications et est souvent utilisée pour comprimer des enrochements en mer destinés aux fondations superficielles de projets industriels ayant des contraintes de tassements ou pour des remblais de quai de zone portuaire industrielle. Multiconsult a plus de quarante ans d'expérience dans l'amélioration des sols par compactage dynamique. Les projets norvégiens d'usine de traitement du gaz de Kollsnes et la raffinerie de Mongstad font partis des projets industriels phares pour lesquels Multiconsult a été impliqué. Ces projets sont particulièrement intéressant pour leurs critères de tassement très sévères et une exigence élevée en terme de documentation.

La première partie de ce document présente les principes théoriques et les philosophies de conception à l´aide du compactage dynamique. La seconde partie de ce document présente l'expérience que Multiconsult a obtenu ces quarante dernières années. Des données de projets sont utilisées pour présenter des recommandations de mise en œuvre du procédé, les tassements et vibrations attendus durant le compactage ainsi qu'un retour d'expérience sur l'amélioration des sols en terme de résistance et rigidité. Enfin, l'équipement courant d'un entrepreneur norvégien sera présenté.

**Keywords:** DDC, Falling weight, Norway, Experience, Recommendations

# 1 INTRODUCTION

Deep Dynamic Compaction (DDC) with falling weight is a traditional and common compaction technique in Norway. DDC has several areas of application and is often used to compact new constructed rock fills in the sea for industrial projects with conventional shallow. DDC is often applicable where conventional compaction is not able to achieve the desired site requirements.

Multiconsult has over 40 years of experience within ground improvement by use of DDC. Kollsnes Gas Processing Plant and Equinor Mongstad Oil Refinery are among the essential industry projects where Multiconsult has been involved over the last four decades. These projects are characterized by very restricted settlement criteria and a high demand on documentation.

# 2 THEORETICAL PRINCIPLES AND DESIGN PHILOSOPHIES

The amount of necessary potential energy to obtain a beneficial compaction is driven by the influence depth, at where the ground improvement is required. Here one should take into account the future use of the site, governing site requirements, time perspective etc. The influence depth has several half-empirical formulations (e.g. Mitchell (2012) or Moyle & Turner (2012)) where Multiconsult has good experience with the method suggested by Hamidi & Varksin (2012):

$$d = \delta \cdot \alpha \cdot \sqrt{WH} \tag{1}$$

Where δ = empirical factor associated to the impact efficiency, α = empirical factor related to ground conditions (damping), and WH = potential energy. W = pounder weight (falling weight) in [tons] and H = falling height in [m].

The impact efficiency is dependent on whether the wire is attached to the pounder during impact or not. A δ-factor of 0.9 is suggested if the wire is attached during impact and 1.2 if the pounder obtain free fall conditions (i.e. the pounder is dropped without wire attached). For the ground conditions, a α-factor of 0.8 is suggested for rock fill and 0.4 for finer material such as silty sands. The product δ·α is often denoted as a single parameter k in other literature. Multiconsult has measured the product δ·α up to 1.00 in new constructed rock fills with several meter thickness.

In addition to the influence depth, the amount of energy per area or volume should be chosen to determine the grid system and the number of crossings and drops. A simple guideline for determining the number of crossing (N) can be formulated as:

$$N = \frac{E(b \cdot \delta \cdot \alpha)^2}{d \cdot n} \tag{2}$$

Where b = grid system spacing in meters, n = number of drops, E = energy per cubic meter and d = influence depth. Please note that N is dimensionless and units are not consistent when determining number of crossing (N) through Eq. 2.

Our experience for obtaining a beneficial compaction is E = 2 to 3 · d, spacing of b = 4 m, number of drop = 6. This often results in 4 crossings such as presented in Figure 1.

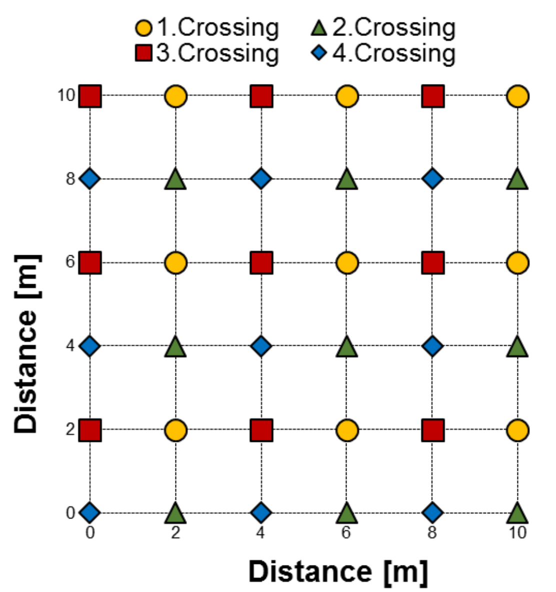


*Figure 1. Recommended grid system and spacing.*

The effect of the last crossings has a less impact on the ground properties and the falling height could be reduced with respect to cost/time aspects. An optimization would then give wide spacing and high energy for the first crossing, both gradually reduced for each crossing (see for instance Kirstein, J.F. et al. (2010)).

An example of the recommended guideline is presented in Figure 2 for a new constructed rock fill in the sea to obtain land for an industry project. The thickness of the rock fill varies from 8 m to 15 m above bedrock. The area was divided into two regions (light grey and dark grey) with different potential energy (2300 / 3200 kNm). Each area contains a grid system with 4 crossings and 4 m spacing with 7 drops in each drop zone. In this project the contractor recorded the final penetration depth for each drop zone which is presented in Figure 3.

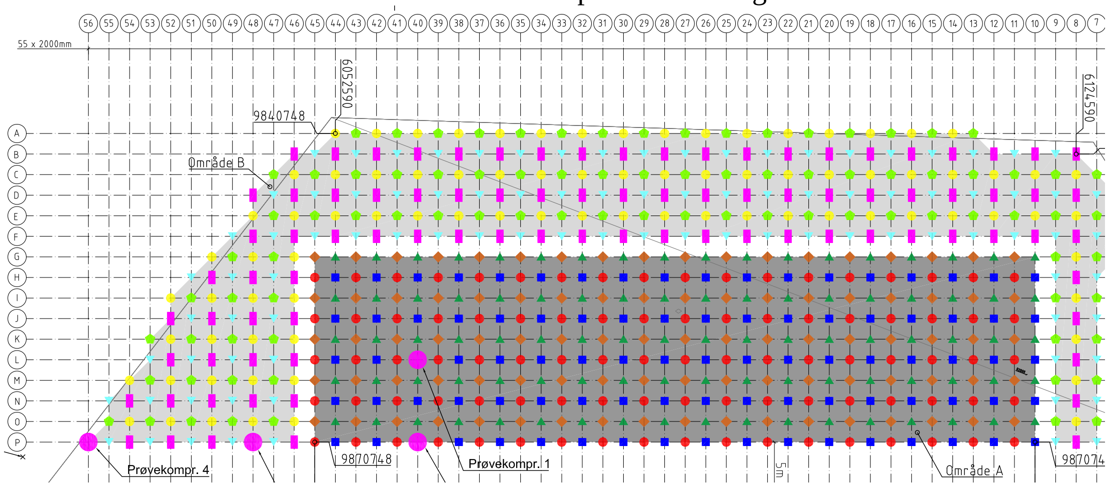


*Figure 2: Planned DDC for an industry area in a coastal region. Light grey = “region A” with 2300 kNm, dark grey = “region B” with 3200 kNm. Grid system with spacing 4x4 m with 4 crossings.*

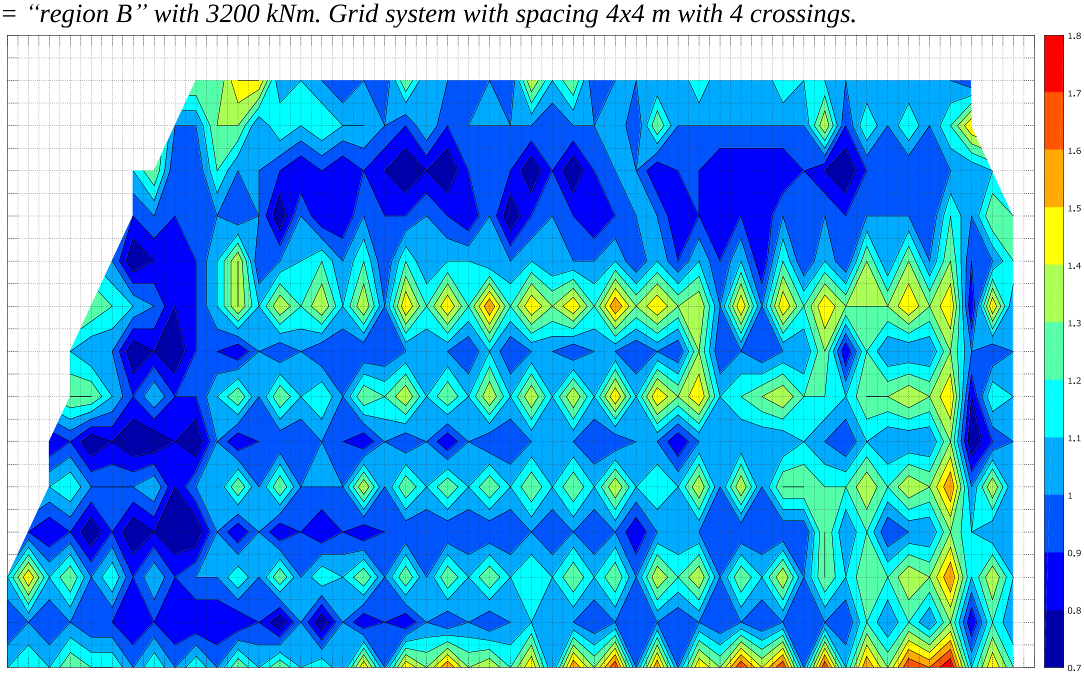


*Figure 3: Recorded final penetration depth in meters for each drop zone.*

### 2.1 Verification of potential energy and number of drops

The outcome of a DDC will be different from each time due to site specific soil conditions. The mechanical soil response and wave propagation properties are key words in addition to wave reflection in harder layers, e.g. bedrock. The equipment the contractor offers would also influence the outcome, e.g. by the δ-factor in Eq. (1). Hence, to verify the determined theoretical potential energy and number of drops it is recommended to execute DDC tests to verify or apply adjustments to the design criteria. This concept is considered as "Design as you go". DDC tests normally consist of 3 – 4 drop zones located in areas where different response is expected. It is recommended to use 10 drops in each drop zone. The penetration into the ground should be measured for each drop, by a levelling device, and presented as shown in Figure 4. From Figure 4 one can observe that after drop number 6 only 5-6 % relative increase in deformation is achieved for each additional drop for this particular example. Depending on the official requirements of the site relative increase below 5-8 % is normally considered as efficient from a cost-benefit perspective.

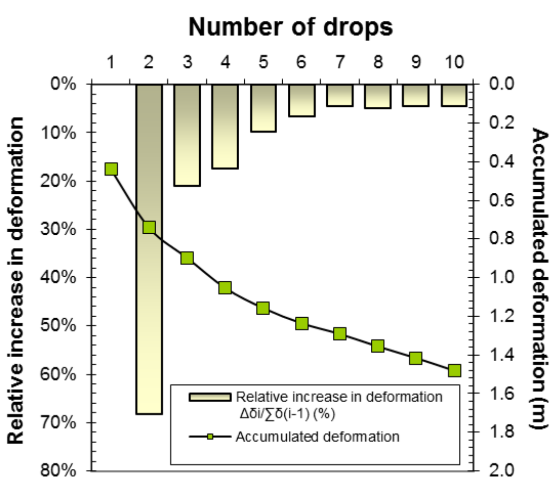


*Figure 4. DDC tests to verify the number of drops and energy.*

## 3 STRENGTH AND STIFFNESS PROPERTIES

### 3.1 Internal friction estimation

The improvement in internal friction can be estimated by assuming that the total energy is transformed purely into plastic work. If the damping forces are disregarded the potential energy would be equal to dynamic forces times the penetration:

$$W \cdot H = Q \cdot \delta \tag{3}$$

Where Q = dynamic force and δ = penetration. Assuming that the impact causes failure in the ground Stordal et al. (1995) has shown that the friction angle can be estimated by Eq. (4):

$$tan\varphi' = 0.15 \cdot \left(\frac{W \cdot H}{0.22 \cdot \delta \cdot \gamma \cdot B^2 \cdot s_\gamma}\right) \tag{4}$$

Where φ' = internal friction angle, B = width of the pounder, $s_\gamma$ = 1-0.4B/L.

Stordal et al. (1995) has reported an increase in the friction of 25 % in rock fill, assuming no change in the attraction. The increase was determined by Eq. (4) and verified by large plate load test. It is also possible to keep the friction constant and back-calculated the attraction increase.

### 3.2 Expected Stiffness and Settlement

In a new constructed fill without any compaction, one may expect large deformation. The deformation is associated to initial and primary settlement caused by the dead weight of the filling itself along with creep strains. Due to the topography in Norway constructed fills may be tens of meters resulting in significant deformation over time in the fill. In addition, further load increase would be associated to the virgin compression line due to the lack of compaction/preloading.

A successful DDC would provoke the deformation within the filling itself and increase the stiffness. One may expect deformation in the order of 5 – 15 % of the filling height in rock fill and according to Stordal et al. (1995) DDC has increased the initial stiffness ($G_{max}$) by 150 % for shallow foundations in a rock fill.

However, even after a successful DDC some creep strains must be expected in the filling. High stress concentration between the particles are expected and may lead to particle break down or particle relocation.

### 3.2.1 Recorded settlement after performing DDC

Multiconsult has been involved in a project where a rock fill was constructed in the sea and DDC was executed with potential energy up to 3200 kNm. Meanwhile, due to changes in the project no buildings were constructed and the site was abandoned for further activities. The height of the fill was 5 to 16 m over a natural layer of sand/gravel with 2 to 7 m thickness above bedrock. An organic layer of gyttja with a thickness of 2 to 4 m above the sand/gravel layer was removed before the filling was established.

Deformation in the filling was measured in 18 points over a period of 5 years after the DDC was executed. The deformation evolution with time is presented in Figure 5. Point 14 to 19 were located at the edge of the filling and point 4 to 11 were located 10 m from the edge. The rest of the measuring points were located further away from the edge, up to 90 m.

The deformation in point 15 to 17 was measured up to 42 mm and ongoing after 5 years. The deformation is assumed to be associated with an unstable toe located in the organic layer, which have not been removed as planned.

The deformation in the rest of the points is assumed to be purely due to creep. The deformation was measured from 1 to 14 mm with a general pattern of 0.05 to 0.1 % of the fill height, increasing towards the edge. Closer to the edge a higher shear stress mobilization would be present, caused by the DDC, resulting in larger creep strains. Approximately 2 years after the DDC no further creep strains were recorded in all points beside point 15 to 17.

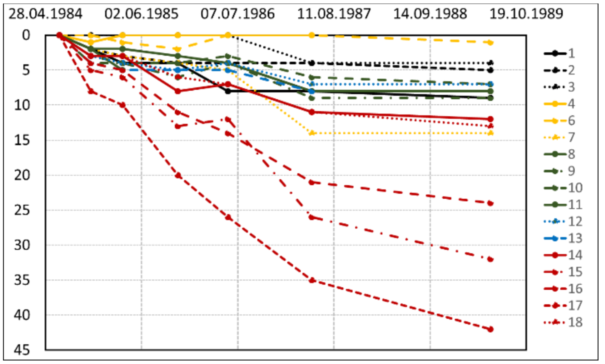


*Figure 5. Recorded deformation with time.*

The volume reduction was determined to be 12 to 13 % and the initial stiffness ($G_{max}$) before and after DDC were measured by surface-wave reflection from 140 - 158 MPa to 243 – 289 MPa (approximately 80 % increase).

## 4 LIMITATIONS

The mechanical response of the soil conditions is governing for the efficiently of DDC. DDC is commonly used in granular material from sand to rock fill but can also be used on finer material. In that case excess pore pressure may develop during execution and settlement will be associated to the excess pore pressure dissipation. However, one may argue of the efficiency compaction in such fine material.

Performing DDC in the winter period is not recommended in regions where snow and temperature below zero is likely to occur. Snow and ice may be mixed together with the soil during the compaction and melt with higher temperature. This would lead to higher void ratio than expected. Frost heave may also be a concern within the winter period.

Close to the edge of a filling efficient compaction can be difficult to obtain and may result in deformation of the slope instead of good compaction. We recommend at least 5 m distance from the edge of the filling to the first drop zone.

### *4.1* Vibrations

The use of DDC in urban areas can be problematic due to ground vibrations. Ground vibrations from DDC can lead to potential damage to adjacent structures in addition to being annoying to people and animal. The ground vibrations would be a function of wave propagation properties of the soil, wave reflection in harder layers, e.g. bedrock, the utilized equipment and impact energy.

The ground vibrations from DDC are often dominated by Rayleigh waves (surface waves). Considering both geometrical and material damping, the vibration velocity (v) at distance given distance (r) can be estimated as suggested by Bornits, G. (1931):

$$\mathrm{v} = \mathrm{v}_0 \cdot \sqrt{\frac{r_0}{r}} \cdot e^{\theta(r-r_0)} \qquad \theta = \frac{-2\pi \cdot f \cdot D}{C_R} \qquad (5)$$

Where $v_0$ = vibration velocity at the distance $r_0$ from the source, $C_R$ = propagation velocity for Rayleigh waves, D = energy loss/damping coefficient. Mayne (1984) has proposed an upper boundary (purely geometrical propagation) for vibration velocities due to DDC:

$$\mathrm{v}_i = 7 \cdot \left(\frac{\sqrt{WH}}{r_i}\right)^{1.4} \qquad (\mathrm{cm/s}) \qquad (6)$$

Where $v_i$ = vibration velocity at distance $r_i$ from the source.

#### *4.1.1* Recorded vibrations

Ground vibration from five different projects are presented in Figure 8. In four of the projects (illustrated with circles), the soil deposit consists of a new constructed rock fill with a thickness of 10 to 30 m above bedrock. In some of the cases a thin nature soil layer of mainly marine sand is located above the bedrock. The last project (illustrated with triangles and squares) consists of a fluvial deposit, which mainly consists of silty sand. Figure 8 shows the vibration propagation as a function of the distance and utilized potential energy. The vibration velocity is increasing with the number of drops due to the increasement in stiffness of the soil. Furthermore, one can observe larger vibrations in the silty sand material compared to the rock fill. This is believed to be a consequence of the silt content causing some dilatancy effects during impact.

Based on our data set one can draw expected boundary lines using Eq. (5) and Eq. (4) for each material. For rock material our data set corresponds fairly well to $\theta$ = 0.055 and $v_0$ = 250 mm/s for Eq. (5) and Eq. (4) if the constant of 7 is substituted by 2. For silty sand our data set corresponds fairly well to $\theta$ = 0.040 and $v_0$ = 700 mm/s for Eq. (5) and Eq. (4) if the constant of 7 is substituted by 4.5.

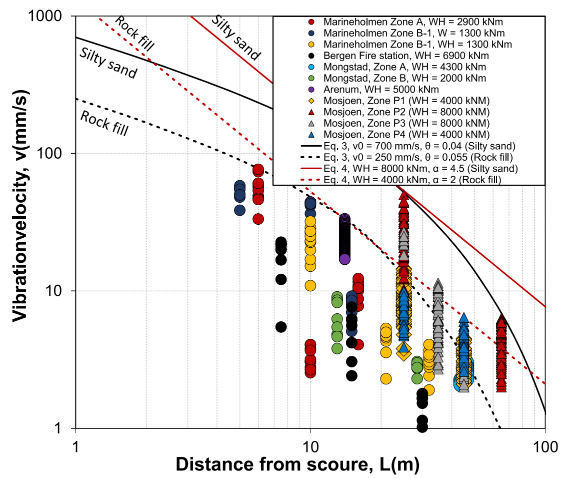


*Figure 6. Recorded vibrations. Circles = rock fill and triangles and squares = silty sand.*

## 5 QUALITY CONTROL AND DOCUMENTATION

During DDC one may expect that the shape of the pounder will changed due to heavy wear. This phenomenon is often the case in rock fill consisting of hard rocks like gneiss and granite. The loss in weight may be severe and the pounder weight should at least be documented before and after executing DDC. Multiconsult has registered weight loss up to one metric ton in several projects. Depending on the original shape of the pounder the impact area may decrease or increase. If shape changes are observed, or the DDC job is very large, one may consider to increase the weight measurements to ensure sufficient potential energy is used.

The contractor is recommended to record the final penetration depth of each crater in data journals. The penetration depth can often be measured directly by the crane operator himself. This information is useful to back-calculate the change in void ratio, general documentation, and observe if any areas deviate from the general response pattern. As a minimum the elevation of the site before and after DDC should be recorded. In this case, one should record the material needed to fill the craters before the next crossing or adjust the surface without any additional material.

The improvement in soil properties should be documented by in-situ ground investigations before and after DDC. The recommended approach is by use of PCPT, but is limited to coarse dense sand or finer material.

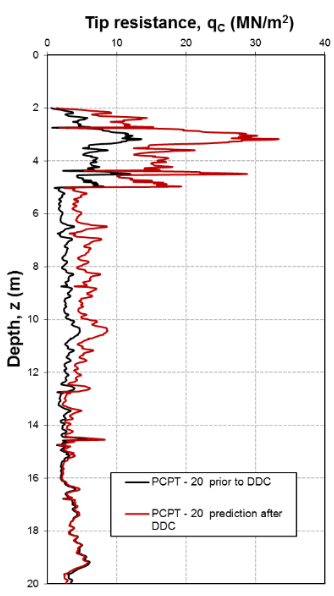


*Figure 7: Improvement in soil properties from DDC - Documented by PCPT.*

Figure 7 presents the recorded tip resistance from PCPT before and after DDC at an industry site in Mosjoen, Norway. The site consists of a man-made landfill of different granular material above the natural seabed which consists of silty sand. The DDC has affected the soil properties to a depth of 14 m.

The fill material in Norway often consists of rock from tunnel driving (drill and blast). In this material the improvement is normally documented by surface-wave reflection or by plate load tests, where the later method is associated to the improvement near the surface. Figure 8 presents data from a site where the improvement has been measured by the down hole method.

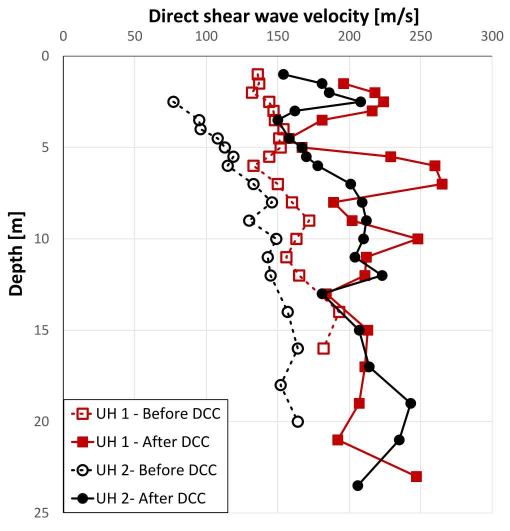


*Figure 8. Direct shear wave velocity from "Up-hole" measurements before and after DDC.*

## 6 SAFETY

Water seepage into the craters will increase the risk of hydrodynamic effects, which may result in flying rock particles relatively far away from the drop zone during impact. Hence, to avoid unnecessary risk, the elevation of the filling should be sufficient to avoid water seepage into crater. In coastal areas in the western part of Norway elevation of +2.5 is normally sufficient, but it should be compared to expected depth of the craters and tide variation or variation in the ground water.

Surface water from rain may be a concern, especially if the water is unable to drain from the surface. The tracks from the crane may lead to areas where rain is accumulated.

DDC in granular fills may cause flying rock particles near the drop zone. However, the safety zone is often defined by the height of the crane. A safety distance of 40 m is normally accepted.

## 7 NORWEGIAN CONTRACTORS

DDC is not ordinary for all contractors in Norway and DDC with high potential energy is limited to a handful. Multiconsult has been involved in projects with potential of 8000 kNm using a steel pounder with a weight of 36 ton. In other projects a less heavy pounder has been used with falling height up to 36 m. The dimension of the pounder is normally 1.5x1.5 m with different height.

## 8 CONCLUSIONS

Although DDC is a simple and practical tool, a proper design should be carried out to give required effects of compactions. Some guidelines to achieve optimal results are presented, such as the ”Design as you go” to adjust the design criteria, as presented in Figure 4. Relative increase in penetration depth below 5-8 % of each drop is normally considered as efficient from a cost-benefit perspective. Our recommendation to obtain a beneficial compaction is E = 2 to 3 · the influence depth, spacing of b = 4 m, number of drop = 6 using grid system presented in Figure 1.

One may expect deformation in the order of 5 – 15 % of the filling height in rock fill. The internal friction may increase up to 25 % and the initial stiffness ($G_{max}$) by 150 % for shallow foundations. Creep settlement in rock fill after DDC has been measured up to 0.05 to 0.1 % of the fill height.

## 9 ACKNOWLEDGEMENTS

The authors are grateful to Equinor Mongstad and Kollsnes Gas Processing Plant for their kind permission to publish the results presented here.

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