Scientific Research Publishing

Open Journal of Civil Engineering, 2023, 13, 282-291
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

A Revisit to the Swedish Wet Compaction Method—A Case Study of the Burvattnet Dam Reconstruction

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How to cite this paper: Rönnqvist, H., Påhlstorp, T. and Gustavsson, D. (2023) A Revisit to the Swedish Wet Compaction Method—A Case Study of the Burvattnet Dam Reconstruction. *Open Journal of Civil Engineering*, **13**, 282-291.
https://doi.org/10.4236/ojce.2023.132021

Received: April 20, 2023
Accepted: June 9, 2023
Published: June 12, 2023

Abstract

The Swedish Wet compaction method allows soil compaction at higher water content than conventional Dry compaction methods and can be used to advantage when difficulties arise in keeping to a certain Dry compaction water content. Wet compaction was frequently applied for dam core soils of glacial till (moraine) up until late 1970s, and despite several advantages it is since no longer used in engineering practice. During the reconstruction of Burvattnet Main Dam in Sweden, the lack of dry core soil together with severe weather conditions made Dry compaction almost impossible. On the basis of laboratory compaction tests performed in compliance with the standard from the 1950s, and field compaction trials on site, this paper describes the steps taken to revisit the Wet compaction method, which made it possible to continue the filling works in keeping with the timeline of the project.

Keywords

Soil, Compaction, Wet Compaction, Laboratory, Field Trial, Glacial Till

1. Introduction

A soil is densified by reducing the void space between particles by applying a compactive effort. Depending on the type of compactor, compaction becomes more effective by the adding of water. In Sweden, beginning in the early 1950s, the practice of compacting at a wet state ensued for dam cores of glacial till (moraine) [1]. This method, collegially known as the "Swedish wet compaction" [2] (hereafter Wet compaction), was first described in [3], which, at the time, was the Swedish standard for the construction of dams. Wet compaction provided an alternative to the conventional Proctor compaction-based approach, which is used for the Dry compaction method (nowadays standardized in [4]). Dry compaction stipulates water content near Proctor Optimum, whereas Wet compaction allows markedly higher water contents. Thus, Wet compaction may be used to advantage in case of difficulties keeping within a set bound of water content, e.g., in severe climate conditions [2]. The 1960s marks the peak of hydropower build-out in Sweden, and in the next decade there was a rapid drop in the construction of new dams [5], and the use of the Wet compaction method became gradually less frequent in favor of the Dry compaction technique [1]. Since the 1970s, Wet compaction has not been used to any meaningful extent.

The almost 80-year-old Burvattnet Dam is located in a tributary of the river Indalsälven in Sweden, in a very remote area that is inaccessible by road. In 2021, the reconstruction of its bottom outlet began and with that a new embankment dam composing a core of glacial till. Almost immediately there were issues with the core soil being too moist, which made conventional Dry compaction with vibratory compactors a very time-consuming process along with many construction shutdowns due to weather. Confronted with crucial delays, alternatives were investigated, and, ultimately, Wet compaction was considered. By switching to Wet compaction, the rate of filling could increase, and the timeline was finally met at the end of the construction season. Based on this case study, this paper describes the steps taken to revisit the Wet compaction method, how the specifications were set, which, on the one hand, were based on field trials, and on the other hand, how compaction data was determined by arranging a laboratory set-up in accordance with the standard dating back to 1958.

2. The Wet Compaction Method

Although similar to puddle clay compaction, the new Wet compaction method was introduced in 1951 mainly in response to the difficulty in achieving Dry compaction of core soils during the short seasonal window for construction works in the northern part of Sweden [2] [3]. These Swedish soils were typically silty and sandy glacial tills (gravelly sands with silty fines), which in practice made Dry compaction nearly impossible unless ideal conditions prevailed. The first dams built by this method were Ligga Dam and Borga Dam in Sweden [6], and, subsequently, several other dam cores were constructed using this technique, mainly in Sweden but also in other countries with similar climate conditions. Other notable examples of wet compacted cores are the 100-m-high Messaure Dam in Sweden [7], and outside Sweden, the 340-ft-high (100 m) Hills Creek Dam in Oregon, US, and the 60-m-high Arstaddalen Dam in Norway [2].

2.1. Specifications According to 1950s Instructions

Wet compaction, according to the instructions in [3], which later was replaced by [8], requires at least 5 passes heavy crawler-type tractors heavy enough to generate a surface pressure of at least 60 kPa. Furthermore, it stipulates water content sufficiently high so that the soil becomes "plastic", which will make the tractor sink 150 to 200 mm into the layer of maximum lift thickness of 250 mm. Sufficient construction control, according to [2], stipulates that a soil is too dry if the heavy tractor penetrates no more than an inch (25 mm), and too wet if it the layer more than about a foot (305 mm). Conventional density tests are not possible because of the difficulties in accurately determine the sample volume since the soft material tend to squeeze together [2].

2.2. Pros and Cons

The Wet compaction method stipulates conditions near saturation of a soil in order to attain a plastic consistency [3]. Compared to Dry compaction, the Wet compaction method offers the following advantages:

- Relatively little homogenization effort is required, and the optimum water content is easy to identify by field trials.
- A homogenous fill with uniform and low permeability (hydraulic conductivity) [3].
- A density with little variation [7].
- Lower secondary settlements (post-construction) than that for Dry compaction (about 50%) [6] [7].
- Lower saturation settlement than that Dry compaction [8].
- Less exhaustive material and construction control.

The potential drawbacks of Wet compaction are:

- The dry density is initially less than that of Dry compaction but will eventually consolidate to an equivalent density [1] [3].
- The primary settlement is greater than that of Dry compaction (between 2 and 4%) [6] [7].
- Possibility of high initial pore water pressures; however, these will dissipate relatively quickly due to the relatively high consolidation coefficient of moraines [9]. For sandy silty moraines, [7] recommended clay content (% < 0.002 mm) less than 10%, preferably about 5%, since even small increases in clay content yield large increases in pore pressures in the wet compacted core.
- Switching from Wet compaction to Dry compaction is inappropriate without potentially lengthy time for consolidation since the Wet compacted surface will not provide sufficient support to the subsequent Dry compacted layer [3].

3. The Burvattnet Dam Project

Burvattnet Dam was completed in 1943 and after almost 80 years of service, in 2021, the reconstruction of its bottom outlet (concrete culvert) began, which included the construction of a new embankment dam. The dam, which is schematically shown in **Figure 1**, measures 12-m in height and almost 50-m in length, and its impervious core comprises silty, gravelly, sandy till (**Figure 2**). It

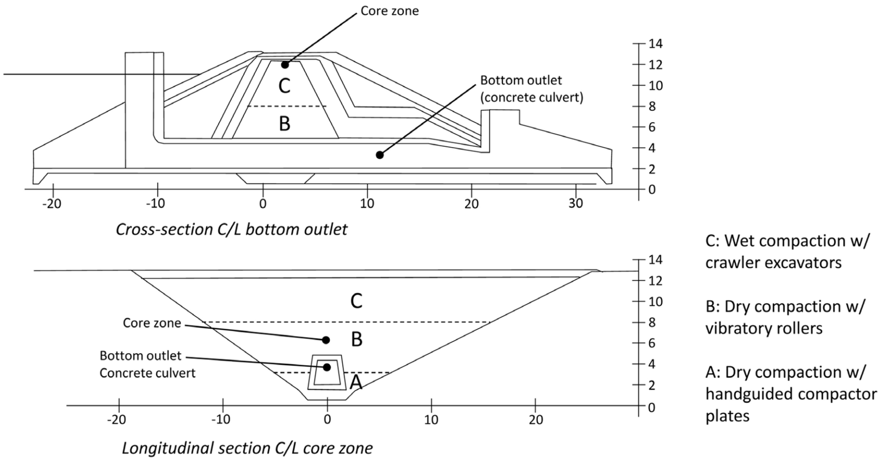

Figure 1. Schematic of the new embankment dam.

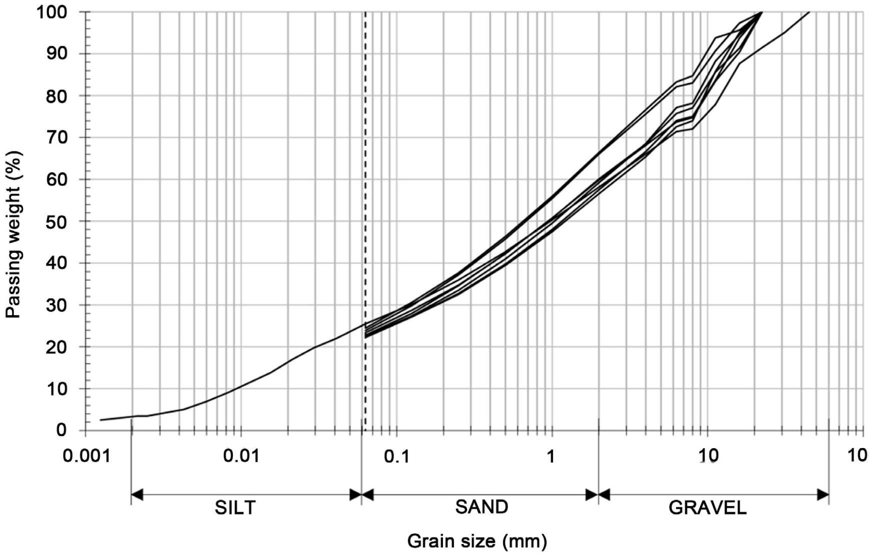

Figure 2. Compilation of particle size distributions of the core soil of glacial till.

is located farthest up in a tributary of the Swedish river Indalsälven near the Norwegian border beyond the reach of roads, thus, equipment and materials had to be transported to site over the reservoir of the downstream located dam, either barged over water or hauled on ice in the winter. Considering its location, proactive steps were taken a year in advance, especially in regards of the core soil so that Dry compaction would be possible once the construction were to commence. However, despite stockpiling and mechanical drying, most of the core soil were still too moist for conventional Dry compaction with vibratory compactors, and for the limited amount of soil that were viable, Dry compaction became a very slow process because of weather conditions.

3.1. Laboratory Compaction Data

According to specifications, the core soil should consist of glacial till with fines content 15% to 40% < 0.063-mm and a maximum particle size D_{100} of 63 mm. **Figure 2** compiles the particle size distributions when D > 20 mm is removed, showing 22% - 25% < 0.063-mm with particle density $\rho_s = 2.72$ ton/m^3, and less than 5% < 0.002 mm clay content. Conventional Proctor-based compaction data, in terms of Dry compaction, were determined using the standard test method with modified effort [4], yielding max dry density (MDD) of 2.25 ton/m^3 and optimum water content (OWC) of 6.5%, as indicated in **Figure 3**. The typical behavior of the soil when dry and wet of optimum is also given in **Figure 3**, which reveals that at water content 2% to 3% above optimum, *i.e.*, in the 9% range, the soil becomes too wet for Dry compaction.

To determine the Wet compaction data, a laboratory set-up was assembled according to specifications in [3], see **Figure 4**. It comprises a loading table with weights to yield a surface pressure of the loading plate of 60 kPa, which equals the stipulated surface pressure from a heavy crawler tractor intended for Wet compaction. The loading plate is arranged with 3 Ø 10 mm drainage holes for the dissipation of pore water pressure during loading. Instructions in [3] stipulates that the soil is placed in a compaction mold in 3 layers, each layer is compressed by 60 kPa pressure until there is no more settlement, and then shaken with a total of 20 blows. **Figure 3** shows the curve for Wet compaction indicating MDD of 2.06 ton/m^3 and OWC of 10.1%. The compacted sample yielding the highest density is shown in **Figure 5** after being extracted from the split mold. Similarly to the curve of Dry compaction, **Figure 3** shows the behavior for the Wet compacted soil if wet and dry of its optimum.

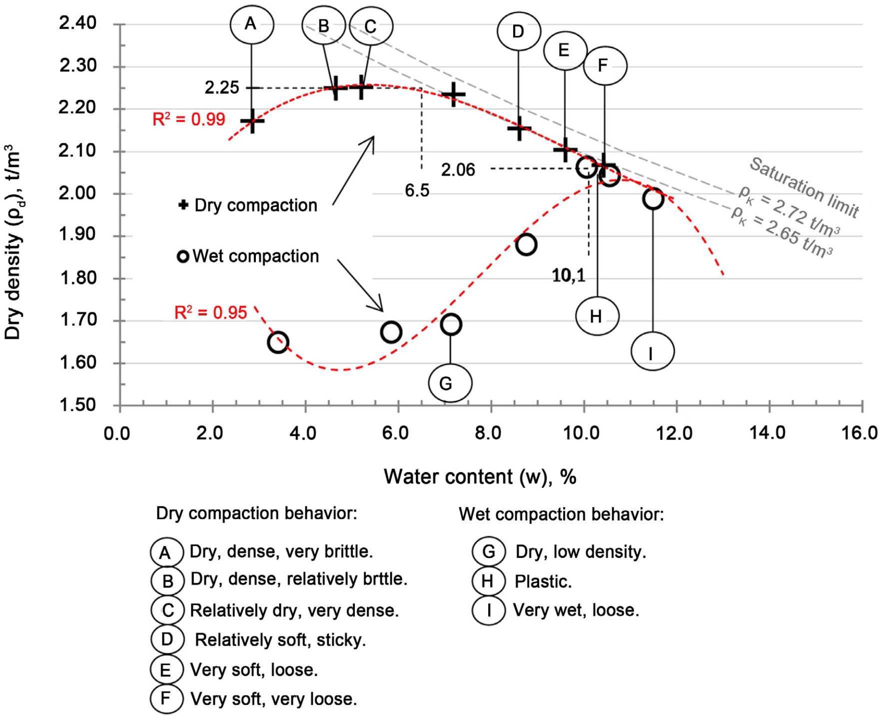

Figure 3. Compaction curves and behavior during testing.

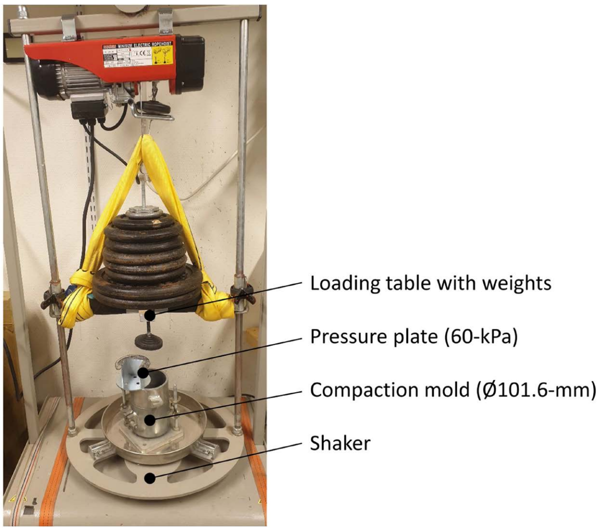

Figure 4. Laboratory assembly for Wet compaction testing.

Figure 5. Laboratory wet compaction specimen at optimal conditions.

3.2. Field Compaction Test

Field tests on site were conducted to confirm the appropriate water content for Wet compaction and determine the required number of passes by the compactor. A crawler excavator of appropriate weight and track surface ratio was used to achieve the stipulated surface pressure of 60 kPa. **Figure 6** shows the difference between appropriate water content (see **Figure 6(a)**) and too wet soil (see **Figure 6(b)**), the former shows when the water content is about 10% and the excavator can travel over the lift without bogging down, whereas the latter shows when the soil is excessively wet (w about 13%) and the excavator sinks through the whole lift.

3.3. Project Specifications for Wet Compaction

Based on the laboratory compaction test and the field trial, the OWC was specified to 10% or just there over when being placed, and MDD of 2.06 t/m^3. The maximum permissible lift size was 250 mm with the requirement of at least 5

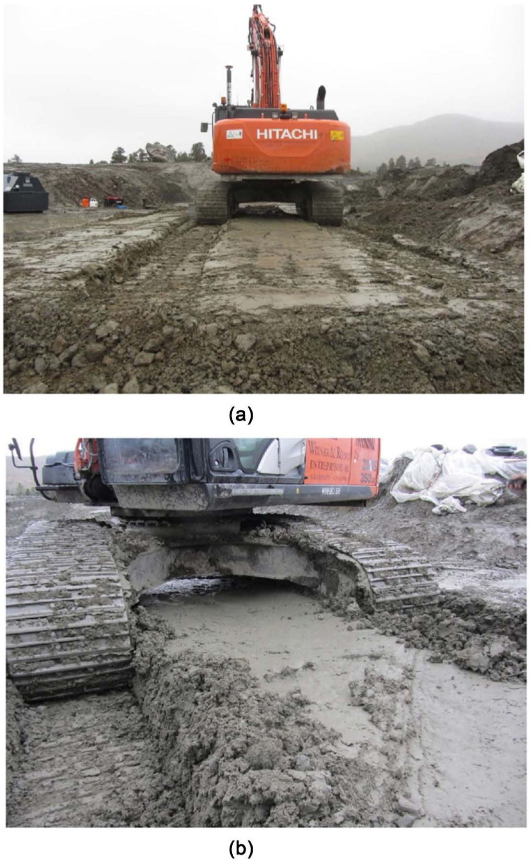

Figure 6. Field trial on site to confirm Wet compaction conditions (a) at about 10% water content there is good homogenization of the soil and appropriate sinking of the excavator, (b) at nearly 13% water content it is too wet causing excessive sinking of the excavator.

passes. Furthermore, instructions stated that once Wet compaction is used, it is no longer allowed to switch back to Dry compaction. The quality control comprised tests of water content, and checks that the minimum number of passes had been performed, and visual checks of compactor depression (*i.e.*, track sinks 150 to 200 mm into the layer). In-situ density tests were not required.

3.4. Application of the Wet Compaction Method

Only a limited amount of the stockpiled core soil was suitable for Dry compaction, and despite attempts of mechanical drying (ripping, plowing, dicing, etc.), the water content rarely went below 8% in the stockpile, which, according to **Figure 3**, ventures into unsuitable soil in terms of Dry compaction. In the borrow areas, however, the water content was in the range of 10% to 12%, and in some cases even higher. **Figure 1** shows that three sections of compaction were executed. The core soil suitable for Dry compaction was utilized up to the crown of the bottom outlet and as far as possible above it. During the initial section (as indicated by "A" in **Figure 1**), lighter hand-guided compaction equipment was used, and above it (as indicated by "B") Dry compaction continued with vibratory rollers. For Dry compaction, the required relative compaction was an average of 95% of MDD, with a minimum of 92%. At this second section, above the concrete culvert, Dry compaction became very time-consuming and nearly impossible to execute, mainly because of the depleting dry core soil, but also due to severe weather conditions that caused frequent shutdowns. Wet compaction was ultimately implemented when about 1/3 of the height (4 m) remained (as indicated by "C" in **Figure 1**). **Figure 7** shows Wet compaction being performed using a 35 ton excavator crawler. This third section was built in about 4 stages consisting of 4 lifts each (1 m per stage). After each stage, the fill required a "rest period" of 3 to 4 days in order to consolidate before continuing with the next stage. During this consolidation period, work would continue with the filter and support fill that surrounds the core zone. The average water content of the wet compacted core soil was 10.2%, and although not a requirement, in-situ density tests indicate on average a relative density of 103% of MDD for Wet compaction. However, density tests are just indications due to the difficulty in accurately measuring the volume. After completed, and standing for about 6 months, the primary settlement of the wet compacted core fill is 30 mm, which amounts to 0.8% of its total fill height, which is well within what is expected.

4. Discussion

Despite its obvious advantages, the use of Wet compaction basically seized after the 1970s, and as put by Löfquist [1], it "went out of fashion", not because of "bad experience from completed dams", but rather due to "a matter of marketing". That is quite true since the alternative, Dry compaction, complies with the well-established Proctor soil compaction principles, which is the international standard [4]. Nevertheless, the idea of Wet compaction originates from the necessity of overcoming tough weather conditions in harsh environments, and perhaps its demise partly had to do with the dwindling extent of large new projects, and with that, a lesser need to manage large filling operations under strict time-constraints. Up until the year 2016, it was still mentioned as a possible compaction method in the Swedish dam safety guidelines; however, it is no longer included in the current version [10]. In engineering practice, the know-how of the Wet compaction method is now limited, but as shown by the case study in this paper, it has obvious utility in demanding conditions and is worthy a revisiting.

5. Conclusions

By performing laboratory compaction tests in accord with instructions from the 1950s, and field compaction trials, as well as experience from the actual construction, the following specifications for Wet compaction were stipulated for the core soil of glacial till of the Burvattnet Main Dam:

Figure 7. Application of Wet compaction of glacial till to the core zone.

1) Compaction by applying 60 kPa surface pressure and at least 5 passes of the compactor (this was achieved by a 35 ton crawler excavator with appropriate track size).

2) Water content 10% or just there over when placed.

3) Maximum lift size is 250 mm.

4) Once Wet compaction is being used, Dry compaction is no longer permitted.

5) Stages of approximately 4 lifts (1 m) can be filled before a short consolidation period is necessary.

6) Quality control comprising water content tests, minimum required passes-checks, and compactor track depression-checks. In-situ density tests are not required.

By applying the Wet compaction method the timeline was eventually met, and the project was successfully completed in 2023. Furthermore, the primary settlements of the wet compacted core were less than expected, only 0.8% compared to 2% to 4%.

Acknowledgements

Gratitude is extended to Vattenregleringsföretagen for kind permission to publish results from the Burvattnet Dam project. The laboratory testing was performed at RQV Geolab a subsidiary of RQV Teknik AB (http://www.rqv.se/).

Conflicts of Interest

The authors declare that there is no conflict of interest.

References

[1] Löfquist, B. (1988) Embankment Dams—Some Steps in the Technical Development. Seminar on Dams 20-21 November 1986, Bulletin No TRITA-VBI-141, the Royal Institute of Technology, Stockholm.

[2] Sherard, J.L., Woodward, R.J., Gizienski, S.F. and Clevenger, W.A. (1963) Earth and Earth-Rock Dams. John Wiley and Sons, New York.

[3] BK (1958) Anvisningar för utförande och kontroll av jorddammar, Vattenbyggnadstekniska byrån BK, 2:a upplagan, Stockholm.

[4] ASTM (2009) Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort. ASTM D1557-09, ASTM International, Pennsylvania, US.

[5] Bartsch, M. (1995) Safety Analysis of Swedish Dams—Dam Performance and Incident Data Analysis. Licentiate Thesis, the Royal Institute of Technology, Stockholm.

[6] Bernell, L. (1984) Foundation, Filling Works and Damages of Embankment Dams. Embankment Dams Seminar 16th and 17th of November 1983, Bulletin No TRITA-VBI-126, the Royal Institute of Technology, Stockholm.

[7] Bernell, L. (1982) Experiences of Wet Compacted Dams in Sweden. International Commission on Large Dams, 14th Congress Rio de Janeiro, ICOLD.

[8] Vattenfall (1988) Jord-Och Stenfyllningsdammar. Vattenfall, Stockholm, Sweden.

[9] ICOLD (1989) Moraine as Embankment and Foundation Material—State of the Art. Bulletin 69, ICOLD, International Commission on Large Dams, Paris, France.

[10] RIDAS (2020) Energiföretagens riktlinjer för dammsäkerhet (Hydropower industry dam safety guidelines). Energiföretagen Swedenergy, May 2020, Stockholm.

Notation

D_x: Grain size at % mass passing (mm).
w: Water content (%). Ratio of the mass of free water to the mass of dry soil.
ρ_s: Particle density (t/m^3). Ratio of the dry mass of the particles to their volume.

Nomenclature

Fines: Amount, by weight, of soil finer than 0.063 mm (European Standard) (%).
MDD: Maximum dry density (t/m^3).
OWC: Optimum water content (%).
1 ton: 1000 kg.