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SIX SIGMA QUALITY IMPROVEMENT OF COMPACTION AT THE NEW DOHA INTERNATIONAL AIRPORT PROJECT

ABSTRACT

The New Doha International Airport project in Qatar comprises amongst other things the construction of a 22-km² reclamation area. The hydraulically reclaimed fill is compacted using a combination of compaction techniques, amongst which High Energy Impact Compaction (HEIC). The process of this novel compaction technique has been optimised using the Six Sigma quality improvement scheme. In this article the implementation of Six Sigma for the compaction process is explained. A direct result of the Six Sigma campaign on compaction was that the average in-situ dry density increased by 8% (from 99% MDD to 107% MDD), and the variance decreased with 56% (from 83 to 36).

INTRODUCTION

The New Doha International Airport (NDIA) in the State of Qatar (Figure 1) will have two parallel runways, 80 terminal gates and a capacity for handling 50 million passengers and 2 million tonnes of cargo per year. It is the first airport to be specifically designed for the use of the new Airbus 380-800 Super Jumbo. The first phase of the NDIA is

scheduled for completion in 2008 at a cost of \$2.5 billion.

The airport is expected to be completed in its entirety between 2015 and 2022 at a total cost of \$5.5 billion.

As part of the first phase, some 22 km² of land must be prepared – half of which is reclaimed from the sea – with 60 million m³ of sand and rockfill. The reclamation should be completed within 24 months, resulting in required productions of approximately 3 million m³ per month. The € 337 million platform reclamation contract was awarded to a consortium of four partners: Qatar Dredging Company, Dredging International, Boskalis Westminster Middle East and Great Lakes Dredge and Dock Company.

COMPACTION WORKS FOR THE NDIA PROJECT

Part of the reclamation work (Figure 2) is the compaction of the fill material to an in-situ dry density as a percentage of the

Above, Satellite photo of the New Doha Airport area under construction.

maximum dry density (MDD). Guidelines of the US Federal Aviation Administration (the FAA) have been followed to draw up the compaction requirements.

Summarised the following fill requirements are imposed:

- Cone Penetration Test (CPT): At least 9MPa cone resistance below mean sea level and never reducing with depth;
- In-situ Dry Density: Above mean sea level, 95% of the Maximum Dry Density;
- Settlement: Maximum 25 mm settlement at a design bearing pressure of 150 kPa.

In order to achieve the required degree of compaction, a combination of three techniques is used in the following order:

1. Hydraulic Compaction: During the deposition of the hydraulic fill, the material is compacted by drag forces of the discharge water by the weight of bulldozers driving up and down in front of the pipeline (Figure 3);
2. High Energy Impact Compaction (HEIC): This novel compaction technique is discussed in more detail in the next paragraph of this article;
3. Conventional Vibratory Roller.

“WHY NEW COMPACTION TECHNIQUES? WHY A SIX SIGMA MANAGEMENT SYSTEM?”

Why was the compaction of the hydraulically placed reclamation fill at the new Doha airport site so unusual, requiring the application of new compaction techniques?

One of the primary reasons was that the contract had an extremely short schedule, requiring over 65 million m³ of fill to be placed in less than 24 months, with many important early milestone handover dates. In addition, different areas of the fill had varying, but very strict, compaction criteria and specific density requirements that were difficult to meet given the nature of the material sourced from the available borrow areas. The sand was coarse and calcareous, often shelly and thus extremely crushable. Heavy dynamic compaction techniques were unusable since they would have converted the material into an unsuitable powder.

After many compaction trials using several different methods, an optimum technique was found. The required results could be

achieved in the short treatment time allowed using multiple passes of an asymmetric (almost square) roller manufactured by the Australian company Broons. The system proved to be extremely efficient as the tractors pulling the rollers could operate two to three times faster than vibrating rollers used for road construction. The reclamation fill had many variables: quality, gradation, water content and layer thickness, each condition requiring a varying number of passes by the rollers. In order to attain a uniform compaction in a non-uniform environment on an extremely congested site, a high level of quality control was needed.

To help meet these challenges the consortium decided to adopt an American management system called “Six Sigma”. The system was initially developed in the United States to improve productivity and quality in the car-manufacturing industry. Former CEO General Electric's Jack Welch has urged other similar industries to adopt

this new system. The consortium Qatar Dredging – Dredging International – Boskalis Westminster and Great Lakes Dredge & Dock applied the novel management programme to a new and very specified field of large-scale compaction. The exercise proved very successful under the careful supervision of a super “Six Sigma” specialist, a so-called “black-belt” inspector from Bechtel. The technical article adjoining describes in more detail how the two new techniques were introduced on site:

- firstly the new compaction system,
 - followed immediately by a new management and “follow-up” system
- We would like to take this opportunity to congratulate all those who successfully and speedily carried out the implementation of these novel techniques and systems.

Marc Stordiau, Qatar Dredging
Bart DeWitt, Boskalis Westminster
Richard Lowry, Great Lakes Dredge & Dock

HIGH ENERGY IMPACT COMPACTION

The High Energy Impact Compaction mechanism is compared with traditional compaction rollers in Figure 4.

The Non-circular compactor module is towed along the ground by a tractor. In every rotation, the module rises up on its contact point with ground and drops to create an impact energy, which provides the compaction. The impact compaction mechanism enables the compaction energy to reach deeper levels than can be reached by static or vibratory compaction methods.

For the NDIA project, the HEIC process is carried out using nine impact rollers produced by Broons Hire (SA) Pty Ltd. Six of these impact rollers are equipped with 8 tonnes weight modules and the other three have 12 tonne weight modules (Figure 5).

Figure 1. Site of the New Doha International Airport.

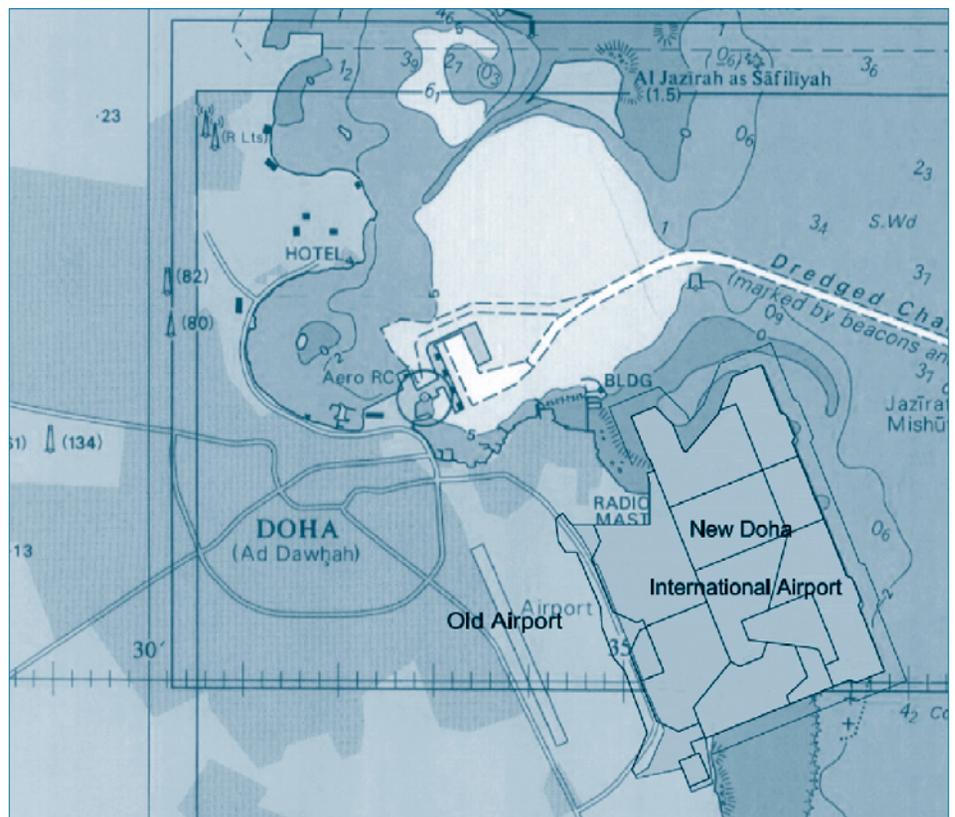




Figure 2. Dredgers at work in front of the reclamation area.

Impact rollers are driven in fixed patterns and reverse their direction from clockwise to counter-clockwise after every ten passes.

This provides a more uniform distribution of the impact energy to the ground and to achieve a better coverage of the compaction area.

The speed of impact rollers should be 10-12 kph, which is the optimum speed for this type of compactors.

Occasional heterogeneity of sand, variability of geo-environmental factors, operator faults, and difficulty in maintaining optimum moisture content adversely affect compaction quality resulting in failures of the compliance tests.

In order to make optimal use of this compaction method and attain a level of control to achieve the specified degree of compaction, the compaction progress was analysed using the Six Sigma management system. The main target of the campaign was to achieve a dry density of minimally 95% of the maximum dry density above mean sea level.



Figure 3. Initial compaction with bulldozers in front of the discharge pipe.



SINA AVSAR

Sina Avsar earned his Bachelor of Engineering and Masters from Istanbul Technical University in 1995 and 1997 respectively. He has worked as a design engineer in the SFS programme of NATO, and in 2005 he completed his PhD at Monash University (Australia). He joined Dredging International as a project engineer at the New Doha International Airport (NDIA) project in August 2005.



MARK BAKKER

Mark Bakker graduated in 1998 from the faculty of Civil Engineering, Technical University Delft, the Netherlands. He has worked as a geotechnical engineer on projects such as the HSL (High Speed Railway) in Holland and also on international dredging and reclamation works in Singapore and Guinea (West-Africa). As of January 2005, he works as a geotechnical engineer for the New Doha International Airport.



GERT BARTHOLOMEUSEN

Gert Bartholomeeusen holds civil engineering degrees from Oxford University, UK and the Ecole Nationale des Ponts et Chaussées, Paris. During his doctoral research at Oxford he specialised in the sedimentation and consolidation behaviour of dredged material. He has worked in the UK, US, France and Romania, before he joined the NDIA project as geotechnical engineer in the beginning of 2005.



JAN VANMECHELEN

Jan Vanmechelen graduated in 1997 as Electromechanical Engineer (Master of Science) at the Karel-de-Grote Hogeschool in Antwerp, Belgium. During the previous 8 years he gained experience in engineering, construction and project coordination. In early 2005 he joined Dredging International where he is responsible for the organisation and follow-up of the compaction activities at the New Doha International Airport site.

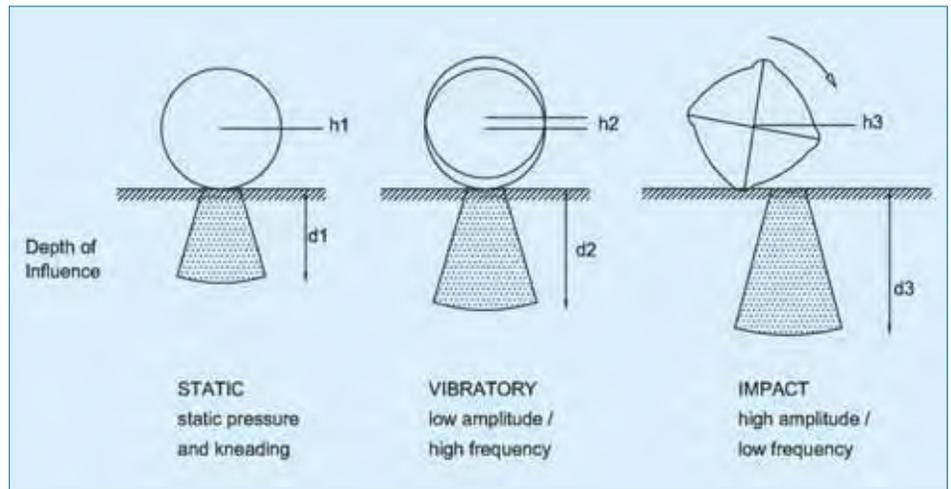


Figure 4. Mechanisms of static, vibratory and impact compaction.



Figure 5. HEIC compactors on the NDIA project; right, a close-up of the compactor.

THE SIX SIGMA APPROACH

The concept of Six Sigma is that of a data driven process management and improvement process. It takes the process under control by decreasing the variability of the input parameters and thereby enabling the process team to control the outcome parameters (i.e. time, quality and cost).

Statistically, the Six Sigma term refers to a process in which the range between the mean of a process quality measurement and the nearest specification limit is at least six times the standard deviation of the process. The statistical objectives of Six Sigma are to centre the process on the target and reduce process variation (Figure 6) (see Slack *et al.* 2004 and Markarian, 2004).

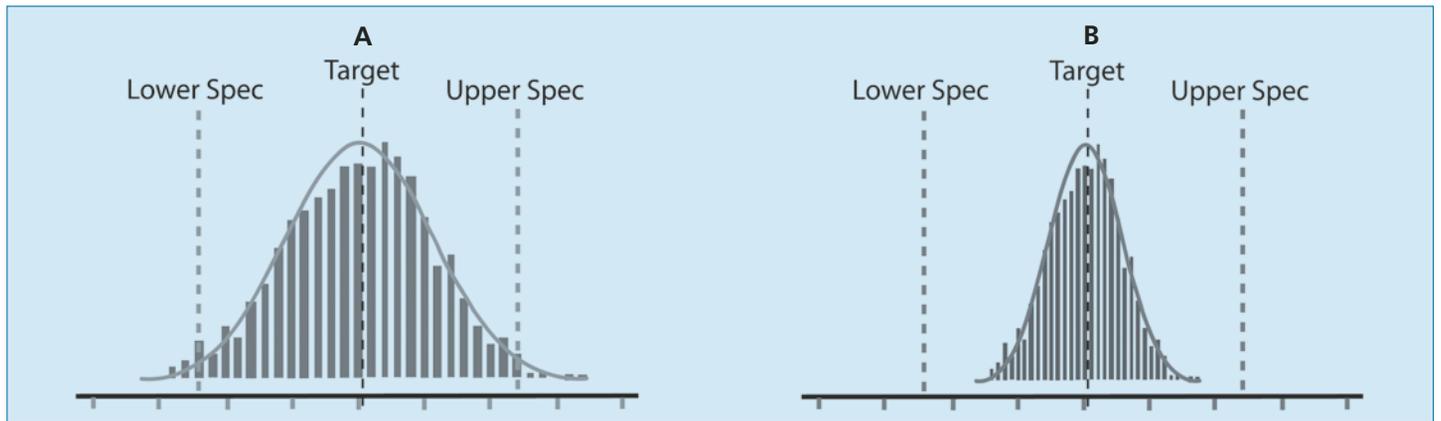


Figure 6. An example for process variability before (A) and reduced variability after (B) Six Sigma implementation.

The goal of the Six Sigma implementation in NDIA compaction process is to increase the compaction quality and to eliminate the results which remain below the minimum requirement for compaction density (in-situ density of 95% maximum dry density).

The Six Sigma Campaign on the compaction at the NDIA project started in August 2005. The Six Sigma team at NDIA was built upon the synergy existing between the Compaction and the Geotechnical Departments. A training course for the Six Sigma methodology was provided by Overseas Bechtel Inc. (OBI).

NDIA compaction Six Sigma campaign can be perceived at three levels:

1. Metric: The target is to achieve the contractual requirement for the compaction quality: in-situ density of 95% maximum dry density.
2. Methodology: DMAIC methodology as defined below.
3. Philosophy: Identify the most important input parameters for the compaction process, measure them, analyse and reduce the variation of the input parameters and take customer-focused, data driven decisions.

A crucial part of the Six Sigma work is to define and measure variation with the intent of discovering its causes and to develop efficient operational means to control and reduce the variation. The expected outcomes of Six Sigma efforts are faster and more robust product developments, more efficient and capable processes, and more confident overall performance (Ingle and Roe, 2001).

IMPLEMENTING SIX SIGMA

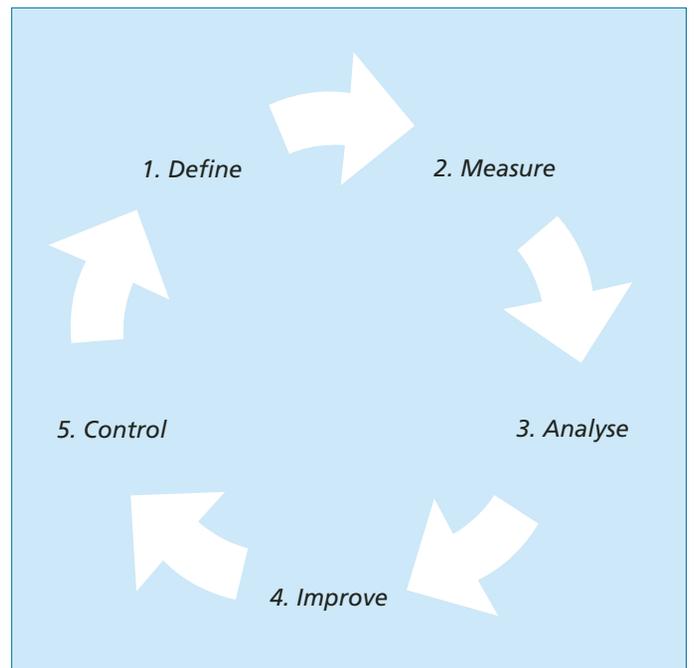
The heart of the Six Sigma implementation of the compaction process at the NDIA site is a five-phase improvement cycle depicted in Figure 7. The so-called DMAIC flow chart: *Define, Measure, Analyse, Improve and Control* is a continuous improvement programme that has become common practice in Six Sigma organisations (Pheng and Hui, 2004). The DMAIC is used as a guideline to ensure that relevant data is collected, analysed, and converted into information. In order to convert data into

information other tools are utilised. The tools used in the framework of the Six Sigma implementation for the compaction process are as follows:

- Compaction Process Map (or flow chart) to identify potential causes;
- Cause & Effect diagram to generate a list of root causes;
- Prioritisation matrix of the most important root causes.

These tools are part of the standard arsenal of Six Sigma tools, and in the following sections a more detailed explanation is given.

Figure 7. The so-called DMAIC – Define, Measure, Analyse, Improve and Control – flowchart.



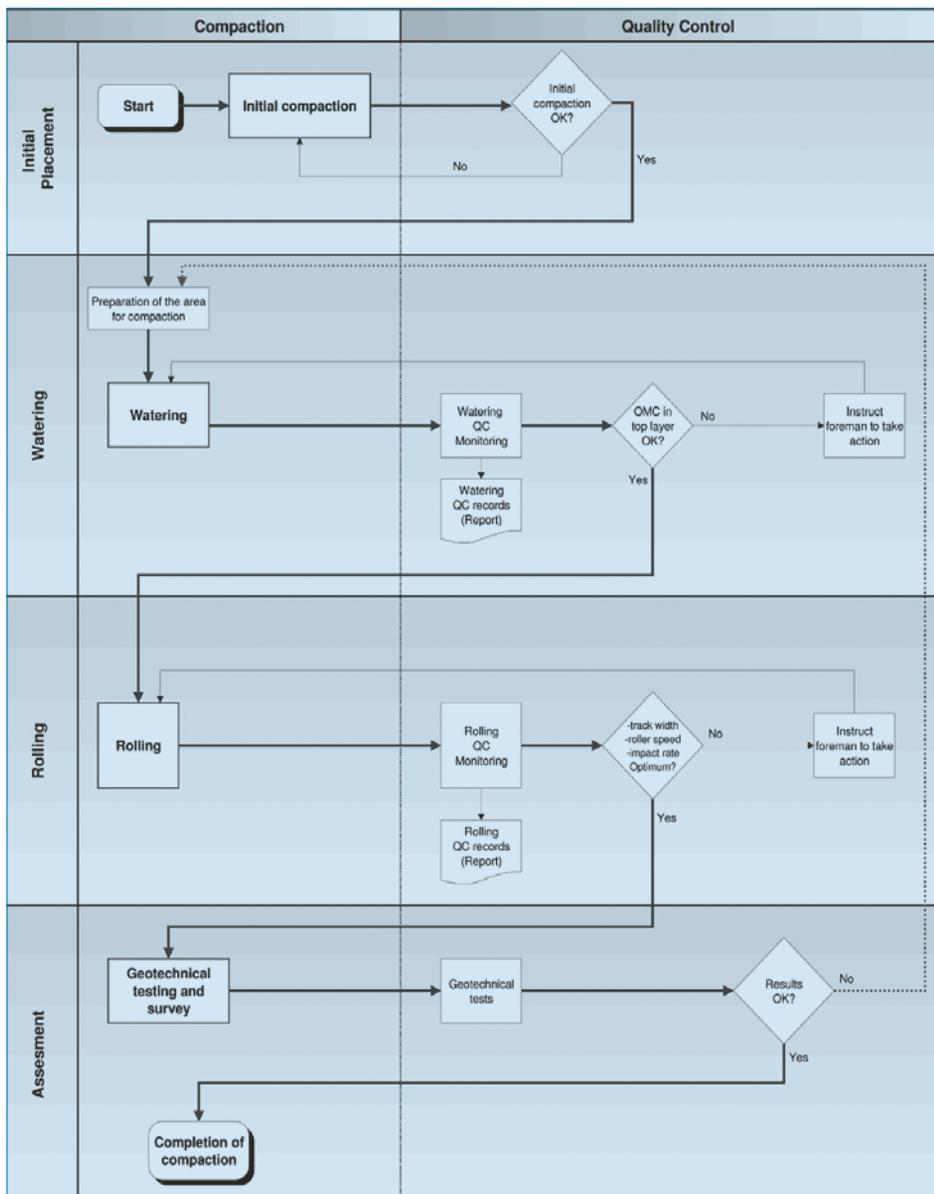


Figure 8. Map of NDIA compaction process.

THE COMPACTION PROCESS MAP

The goal of a process map (or simply flow chart) is to give a detailed understanding of a process prior to improvement. The act of recording each stage in a process quickly shows up poorly organised flows, and light is shed on the internal mechanics of an operation where no procedure exists to cope with a particular set of circumstances.

In Figure 8, the NDIA Compaction Process Map is presented. The compaction process has been subdivided into the following critical stages:

- Initial compaction or hydraulic compaction;
- High Energy Impact Compaction (HEIC);
- Watering to optimal moisture content (OMC);
- HEIC compaction;
- Assessment by means of geotechnical testing.

Quality Control (QC) has been included in each of the stages. The QC jobs are executed by quality controllers who are based in the field and stay in direct contact with the foremen of the respective operations to take immediate action where needed.

The compaction process as a whole involves the collaboration of three different departments, namely reclamation, compaction, and geotechnical department. The clear mapping of the process has created clarity to all the parties involved.

THE CAUSE-EFFECT DIAGRAM OF THE COMPACTION PROCESS

A particularly helpful tool in searching for the root causes of problems is the Cause-Effect diagram (or Fish-bone diagram, also known as Ishikawa diagram). It is done by asking the what, when, where, how, and why questions, as generally done throughout a Six Sigma programme, but this time some possible “answers” are added in an explicit way. Furthermore, Cause-Effect diagrams can also be used to identify areas where further data is needed. The Cause-Effect diagram of the NDIA Compaction Process, depicted in Figure 9 has been drawn up in four steps:

- *Step 1 – List the problem in the ‘effect’ box:* Not meeting the compaction requirements as defined in the contract;
- *Step 2 – Identify main categories for causes of a problem:* Manpower, Machines, Materials, Methods, Measurements & Geo-environment;
- *Step 3 – Systematic fact-finding & group discussion:* During brain-storming sessions anything that may result in the effect of not meeting the contract requirements is put down as a potential cause;
- *Step 4 – Record all potential causes under the relevant category:* After recording and categorisation of the all the causes, each item, e.g. roller pattern, is discussed to combine and clarify the causes.

Eventually, the diagram gives an overview of all the “root causes” that could have an effect on the compaction. Not all of these root causes have the same impact, and the most important root causes are selected to build up a prioritisation matrix that is discussed in the following section. After thorough investigation, the following root causes were found necessary to prioritise in

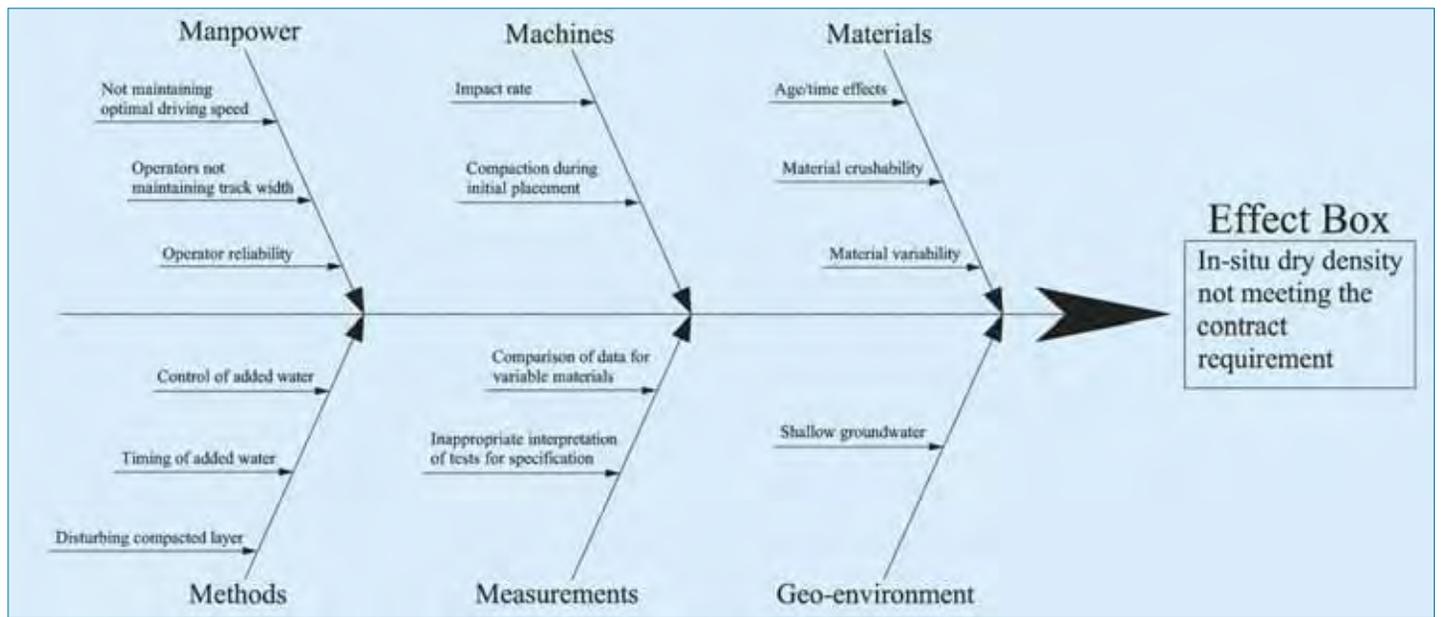


Figure 9. NDIA Compaction Cause-Effect diagram.

the compaction process:

- *Category Manpower:*
 - Optimal driving speed;
- *Category Machines:*
 - Impact rate;
- *Category Methods:*
 - Roller track width;
 - Timing of added water.

PRIORITISATION MATRIX

The prioritised root causes become so-called “upstream process indicators” (often denoted by the symbol X_s). Controllable/measurable systems have to be developed and put in place along with the definition of optimum values. The controllable parameters of the compaction process, roller speed, impact rate, roller track width and the timing for the water spraying are the key upstream process indicators. The optimum values and specification ranges for these parameters are given in Table I.

For the compaction process at the NDIA project, quality controllers have been appointed to continuously measure the upstream process indicators:

- Roller speed,
- Impact rate,
- Roller track width,
- Timing for water spraying.

The measurements method applied on the compaction process are conceptually explained in Figure 10. As indicated in the Compaction Process Map (Figure 8), the quality controllers reported directly to the

respective foremen when readings outside the specification range were measured. The data is statistically analysed on a daily and weekly basis, following the DMAIC improvement cycle given in Figure 7.

Table I. Optimum values of process indicators X_s

Upstream process indicators (X_s)	Optimum Value	Specification range
Roller speed	11 kph	10-12 kph
Impact rate	2 impacts/sec	1.8 – 2.2 impacts/sec
Roller track width	2.6 m/track	2.4-2.8 m/track
Timing of water	20 min/watering session	15-25 min/watering session

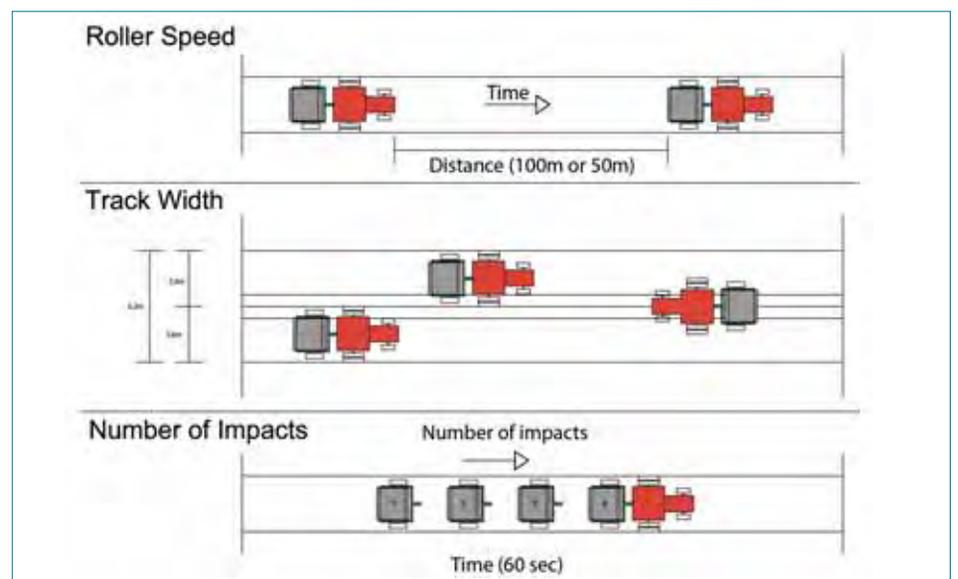


Figure 10. Upstream process indicators measurement methods.

COMPACTION PROCESS IMPROVEMENT AFTER IMPLEMENTATION OF SIX SIGMA

To illustrate the improvement that has been achieved by the implementation of Six Sigma on the compaction process, in-situ dry density data of two compaction areas are presented here:

- HEIC Test Area: Six Sigma quality control was not applied (as denoted by "Before" in Figure 8);
- Area B: This is the area where the quality controllers have been appointed during the Six Sigma campaign to monitor the compaction process for 24 hours/day (as denoted by "After" in Figure 8).

The in-situ dry density is the bottom line "effect" of the Cause-Effect diagram, as given in Figure 9. Since, it is also a contractual requirement, it is the best variable to illustrate the influence of Six Sigma on the compaction process. It is noted that here, the in-situ dry density is expressed as a percentage of the maximum dry density (% MDD).

In order to show what the variation of the in-situ dry density under uncontrolled (HEIC Test Area) and Six Sigma controlled conditions (Area B) is, a control chart is employed. Such a control chart is in fact two charts in one:

- Chart 1 is used to control the sample average or mean \bar{X} ;
- Chart 2 is used to control the variation within the sample by measuring the range R .

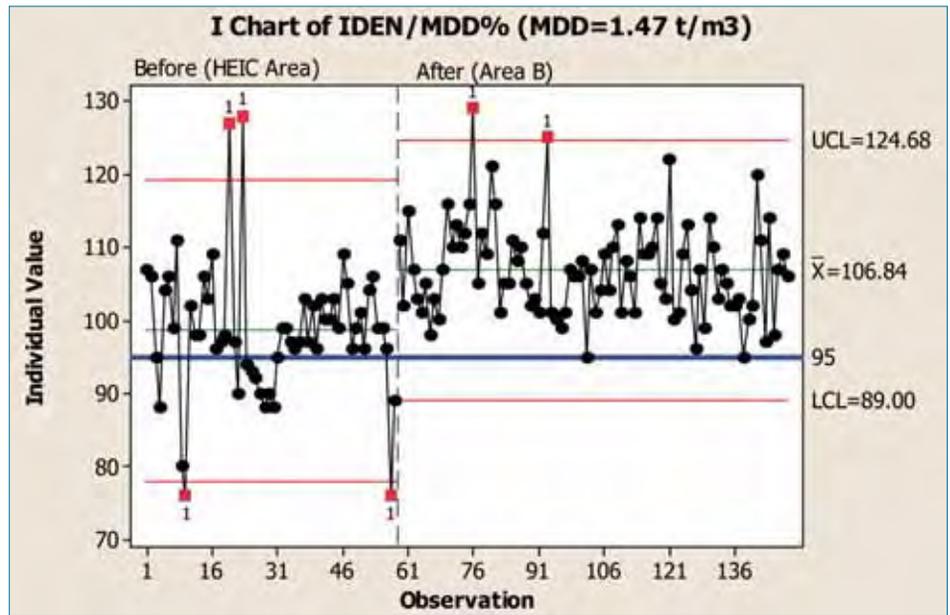


Figure 11. Control chart – In-situ dry density HEIC Test Area and Area B.

The control chart for the in-situ dry density measurements for both areas (HEIC Test Area and Area B) is plotted in Figure 11. In the chart, changes in the mean in-situ dry density, denoted by \bar{X} , are given.

The observations to the left of the vertical dashed line are the observations done in the uncontrolled HEIC Test Area, while the observations to the right are done in the Six Sigma controlled Area B. The mean in-situ dry density for the HEIC Test Area shows a drift, while for the controlled Area B a much more stable and higher average is observed. In the lower chart, the range R of each sample is plotted –

calculated as the difference between successive values. For the HEIC Test Area it is clear that the variability of the process is changing significantly, even around observations where the process average remains rather constant. For the Six Sigma controlled observations (Area B) the variability is much more limited.

Figure 12 shows the output of the statistical analysis of the data of the HEIC Test Area and Area B. The mean in-situ dry density went up from 99% MDD to 107% MDD after applying Six Sigma, and the variance went down from 83 to 36.

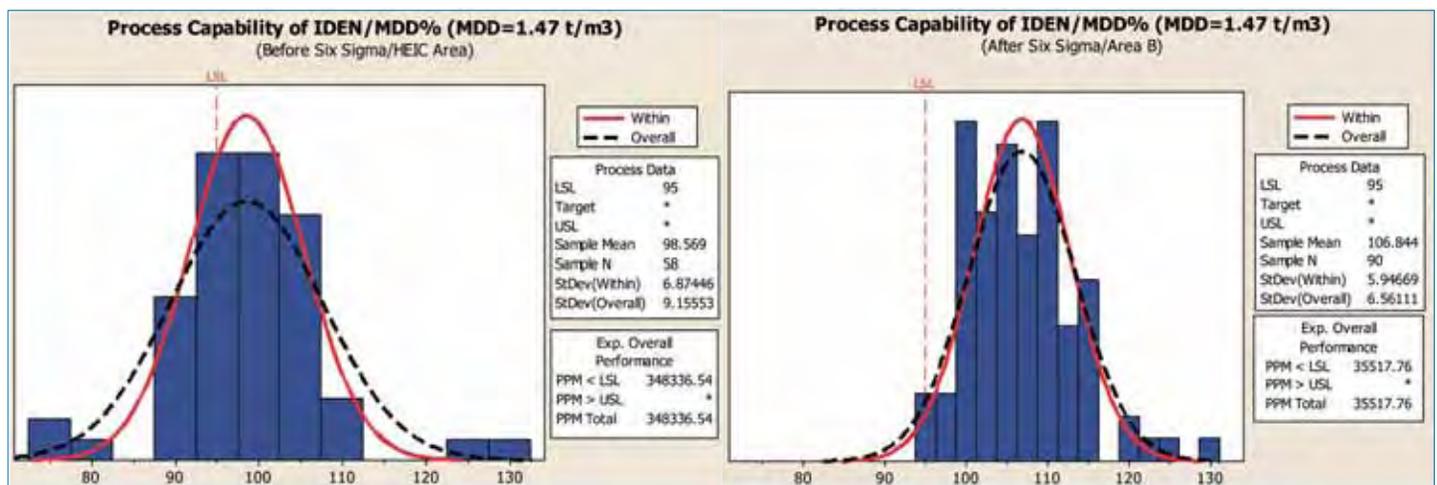


Figure 12: Statistical comparison – In-situ dry density HEIC Test Area and Area B.



Figure 13. An aerial overview of the New Doha International Airport site. High Energy Impact Compaction with rollers was checked by the Six Sigma quality management system.

CONCLUSIONS

A direct result of the Six Sigma campaign on compaction was that the average in-situ dry density increased by 8% (from 99% MDD to 107% MDD), and the variance decreased with 56% (from 83 to 36).

Roller speed and track width have been identified as the most important upstream process indicators, having a direct influence on the in-situ dry density. Six Sigma has allowed for a good control of these variables and helps ensuring that the contractual requirements are met (Figure 13).

Six Sigma is much more than just a number crunching exercise. The visual and measurable outputs of Six Sigma allowed all the team members, from workers to management, to have a clear understanding of the processes involved, and their importance and contribution in delivering a solid fill, compacted within the contract specifications.

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