Paper Title: Smart Bollard: Real-time Monitoring of Mooring Line Loads for Enhanced Port Safety and Efficiency

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The Smart Bollard is a groundbreaking innovation designed for permanent quay installation to measure the loads on mooring lines. By sensing and translating the structural movement caused by mooring line tension, this device provides real-time data on mooring line loads to the port authority, terminal operator, or vessel itself. Unlike conventional bollards, the Smart Bollard offers accurate load measurements and helps mitigate risks associated with high waves, strong currents, and gusts during inclement weather conditions. Its utilization ensures enhanced safety and a better understanding of mooring forces, preventing accidents and detaching of ships from the quay.

Over several years, the Smart Bollard has undergone extensive development, testing, and calculations. Rigorous research and engineering efforts have been dedicated to its design, ensuring reliability, accuracy, and durability in demanding maritime environments. Numerous prototype iterations were refined through iterative testing and optimization processes. Finite element analysis and computational simulations were employed to validate the structural integrity and performance of the Smart Bollard under varying load conditions. These meticulous development stages have resulted in a robust and effective solution that meets the demanding requirements of the maritime industry.

The Smart Bollard offers a comprehensive monitoring solution through its MoorControl software, displaying and storing essential data. Port authorities, terminal operators, and vessel owners can access clear information on mooring line loads, enabling more efficient port operations. This technology becomes increasingly crucial with the advent of larger vessels and more severe weather conditions, providing valuable insights into mooring loads.

The dashboard interface of the Smart Bollard system presents crucial information for optimized utilization. Data on the load on the bollard, line direction, line angle, tide level, weather conditions, and vessel history (AIS data) are displayed and logged for future analysis. Administrators can easily add users and set alarms through a user-friendly interface. Additionally, the system provides an API for seamless integration with other systems, offering accessibility to all relevant data for the Port Authority, terminal operator, or vessel operator.

The benefits of implementing the Smart Bollard include increased safety for operators and assets through real-time load monitoring, improved efficiency of vessel movements based on a complete overview of mooring forces, and potential accommodation of larger vessels. Moreover, the gathered data and predicted forces have the potential to reduce the need for expensive resources like tugs. Cumulative data on berths and vessels collected by the Smart Bollard can drive port improvement projects and continuous enhancement of operations and processes.

The Smart Bollard can be connected via ethernet or wireless operation. Ethernet connection requires a separate switch box for data gathering and transmission to the cloud, while wireless operation necessitates the installation of a gateway on-site. Data is sent to the cloud (AWS) and accessed through a user-friendly portal, which also provides weather and current information and a vessel database. Integration with other systems is made easy through a standard API.

The successful trial of the Smart Bollard at the Port of Rotterdam, in collaboration with Straatman and the Port of Rotterdam, has demonstrated its efficacy in improving port efficiency through digitization. Nowadays, we installed 6 pcs of Smart Bollards at the ECT Delta terminal and 108 pcs along the new Prinses Amalia quay of the Port of Rotterdam, further enhancing port safety and operational excellence. Besides, we are currently testing the Smart Bollard at Port of Valencia (MSC Terminal) and Port of Antwerp.

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2. Introduction

The team have been working on the development of the Smart Bollard since 2018. The design of the Smart Bollard is based on a "normal" bollard (T-version). However, the design has been modified in such a way that the bollard shaft can move within safe margins. This movement is facilitated by the waves in the footplate and is measured in three directions with high-precision sensors mounted inside the bollard.

The Smart Bollard has been tested many times in our test bench (see timeline in Appendix I). The measurement results show that the bollard movements are well-measured. Subsequently, the bollard was installed as a pilot at ECT Europahaven (DDN terminal). After installation, the bollard was tested using load cells on the mooring lines of moored vessels and by means of a test frame from Bollard Proof.

Based on the tests, the conclusion is that the Smart Bollard meets expectations; the deformations of the bollard run linearly as expected and can be directly converted into a force, angle, and direction. The calculation is based on the FEM model, which achieves a measurement accuracy of +/- 5%. Through calibration in the test bench and testing with the test frame, the formula has been refined. Due to this improved formula, a demonstrated measurement result of +/- 1 ton over the measuring range of 100 tons has been achieved. The calibration is required per type of bollard (and not per individual bollard).

In practice, the measured value may differ (e.g. due to the position of the truss on the bollard); the expected accuracy of the measurements in practice is:

- Strength +/- 5% (Measurement accuracy Tested bollard is 1 Ton)
- Horizontal direction +/- 10 degrees
- Vertical direction +/- 20 Degrees

3. Development of Smart Bollard

The development started with measuring the force on the anchor bolts of an existing bollard. In this development process, we found that measuring existing bollards in this way is not accurate enough and that the costs are too high. That's why we decided to focus entirely on designing a new bollard. Several challenges had to be overcome:

- Design?
- How to measure?
- Reliability?
- Accuracy?

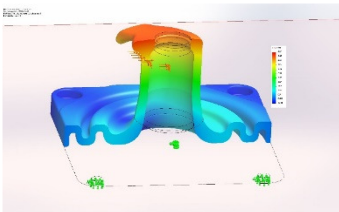

Figure 1 FEM calculation

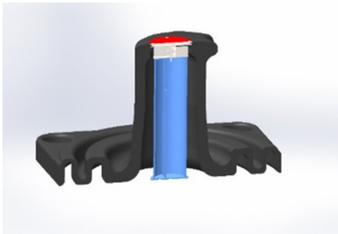

Figure 2 3D drawing Smart Bollard

3.1 Design

The design is based on a "normal" bollard (T-version). However, the design is conceived in such a way that the bollard shaft can move within safe margins. This movement is facilitated by the waves in the footplate and is measured in three directions with high-precision sensors mounted inside the bollard. Based on these three measurements, it is possible to calculate what the force on the bollard is and in which direction and angle this force is exerted on the bollard.

4. Test in test bench

Inventor has its own test facility. However, due to the dimensions of the bollard and the test bench, there are limitations. The bollard can only be loaded at a vertical angle of 0, 22.5 and 45 degrees. And in the horizontal direction, testing in 0 and -9/+9 degrees is possible.

This means that the formula for calculating the values cannot be fully tested in the current test bench. This was solved during the pilot by testing with a test frame from Bollard Proof.

Test set-up:

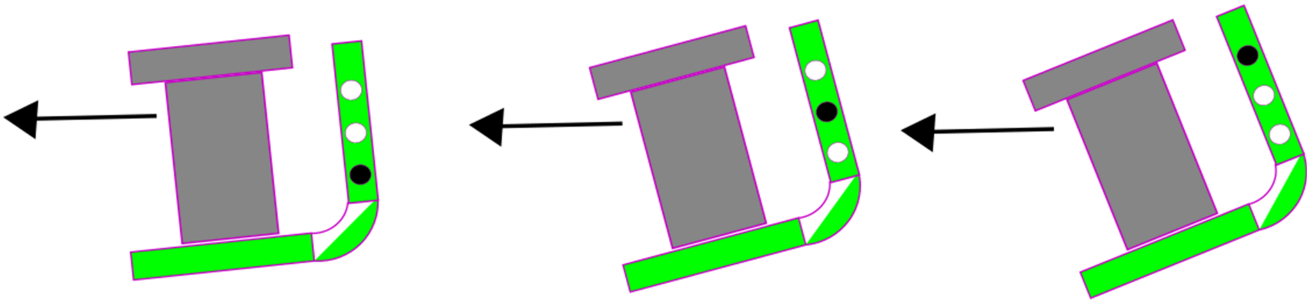

Figure 3 Test positions in testbench

The Smart Bollard has been tested many times in our test bench. The measurement results show that the bollard movements are well-measured. As expected, these displacements are linear and can be directly converted into a force, angle, and direction. The measured values can also be reproduced. The measurement results are set out in Annex III.

We therefore have the following conclusion after testing:

- Load measurement more accurate than expected
- High reproducibility of measurements
- Heat sensitivity (sunlight) measurable, deviation nil.

Figure 4 Bollard in teseting machine

4.1 Achievable tolerances demonstrated based on testing

- Maximum deviation on load: +/- 5%
- Maximum deviation horizontal range: +/- 10 degrees
- Maximum deviation vertical range: +/- 20 degrees

4.2 Conclusion

- ➔ A clear linear relationship between measured values and applied force to the bollard.
- ➔ Absolute values of the measured values at different angles are close to each other.
- ➔ Deviation at low force detected. Bollard "hangs" in the test bench and must first be pulled up.
- ➔ Shown that the bollard works with this principle.
- ➔ The measuring range of the test fixture is limited. More data can be collected through measurements in practice, which can further increase the accuracy of the measurements.

5. Pilot and measurements at ECT

After the successful tests in the test bench, the Smart Bollard was installed as a pilot at ECT Delta, bollard 179, January 2021. This bollard position is used very regularly and thus provides valuable measurement data.

Various tests were carried out during the pilot. A number of measurements have been taken by KRVE with a load cell between bollard and line. In addition, measurements were taken with a test frame from BollardProof. BollardProof has placed a test frame over the bollard to test it with pure load in various directions and angles up to the maximum load of 100T.

All test results have been analyzed in order to prove the efficacy and to further optimize the formula for force calculation. This calibration was performed to refine the formula based on calculations with the FEM model.

It is expected that the calibration will only be required per bollard model, and not per individual bollard. However, we do intend to test each bollard in the test bench before installation, during this test the deformation is measured. This measurement shows that the bollard in question falls within the specifications.

5.1 Placement of the bollard

The Smart Bollard is placed on an existing anchor pattern. The existing bollard has been removed. The base plate and anchor pattern of the Smart Bollard are larger than a standard bollard. In order to be able to use the existing anchor pattern, an adapter plate has been used. The bollard and adapter plate were pre-tested on 150T in the test bench.

Findings during posting:

1) Detaching existing bollards is labor-intensive
2) The Smart Bollard was completely painted. Lacquer under the nuts is not advised.
3) The potholes of the Smart Bollard are not wide enough for hydraulic tools -> Adjust in design.

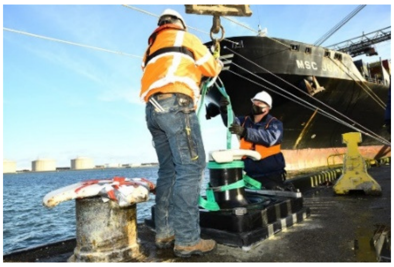

Figure 5 Installation of first Smart Bollard

5.2 Risks

1)	Bollard succumbs	-> Design FEM Design Load 200% SWL -> Bolder tested at 150% in test bench -> Material certificates
2)	Anchor bolts fail	-> Inspection of anchor bolts during installation (retrofit) -> Risk seems small when applied to new quay.

6. Load Cell Test (KRVE)

In collaboration with the rowers (KRVE), various measurements were taken in practice. To do this, a load cell was mounted between the line to compare the actual force on the bollard with the calculated value. These measurements with the load cell are useful to gain more insight into the value of the calculated load on the Bolder.

The comparison of the measurement data was made difficult by the fact that the load on the bollard is reported in a fixed rhythm of 15 seconds and the load cell does not log in the same way (different frequency). The rhythm of the bollard is used as a guideline and the measured values of the load cell are interpolated to the measuring time of the bollard.

6.1 Findings

Findings during the test period at the ECT:

1) Bollard shifts on adapter plate -> Due to shifting, sometimes measurement deviation;
   -> Shear footplate on adapterplaat
   -> Not expected when installing with non-shrink mortar
2) Do not line against the cap -> Line bollard doesn't always creep up
   -> Deviation in readings too large (design change Forcing steed upwards by adjusting shaft)
3) Measured values explainable and consistent

6.2 Conclusion

- ➔ Clear linear relationship between loadcell and bollard measurements
- ➔ Deviation detected by:
  - Minimal shifting of bollard on adapter plate
  - Deviation in formula (improved based on these measurements)
- ➔ With the right formula, the load with smart bollard is easy to measure
- ➔ Still uncertainty about measurements in various other directions (not being able to test)

7. Test with test frame (BollardProof)

To be able to further validate the measurements, the bollard was pulled with a test frame at different angles and loads. As a result, we know exactly at what angle and load the Smart Bollard has been pulled. This will be compared to the data from the Smart Bollard, so that we can say with certainty that the SB is a well-functioning product.

7.1 Frame description

To apply the right force at the right angle, a test frame from Bollard Proof Ltd will be used. This test frame has a maximum tensile force of 150 tons. The vertical range of the test frame is 0-75° in 15° increments. The horizontal range of the test frame is -30.0 and +30°. See the images below for clarification.

Figure 7 Testframe to test Smart Bollard

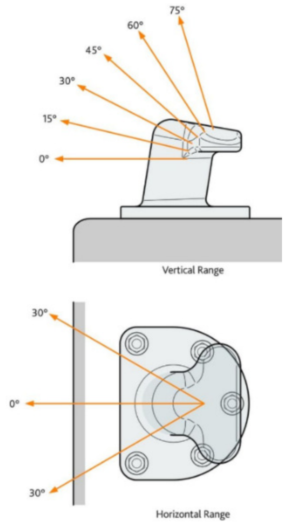

Figure 6 Test positions

7.2 Conclusion

- ➔ Bollard shifts on the adapter plate, this can cause deviations in measurements. Good results are achieved by "reset" the measured values
- ➔ Formula has been further improved based on measured values
- ➔ With the right formula, very high accuracy can be achieved (+/- 1 ton)!

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8. Dashboard/Readout

8.1 Data communication

The Smart Bolder in this pilot sends data via LoRa. A measurement is taken every 15 seconds. Every minute, these measurements are sent to an online portal. The portal provides a clear dashboard that has been specially developed for this application.

LoRa is an effective solution for the pilot. For new-build quays, a wired connection (ethernet PoE) can be chosen. This allows the data to be collected by a PLC that can forward it to an online portal.

8.2 Dashboard

In order to be able to use the Smart bollard optimally, data must be combined. For example, what is the relationship between wind, tidal and line loads? In addition, it is interesting to register which ship is docked and for what period.

The dashboard that has been developed specifically for the Smart bollard now provides:

- ➔ Ship database (based on AIS data from FactoryLab)
- ➔ Tide (via API from PoR)
- ➔ Weather (via API from PoR)
- ➔ Line Loads, Direction and Angle on Smart Bollard
- ➔ Graphs with historical data
- ➔ Location

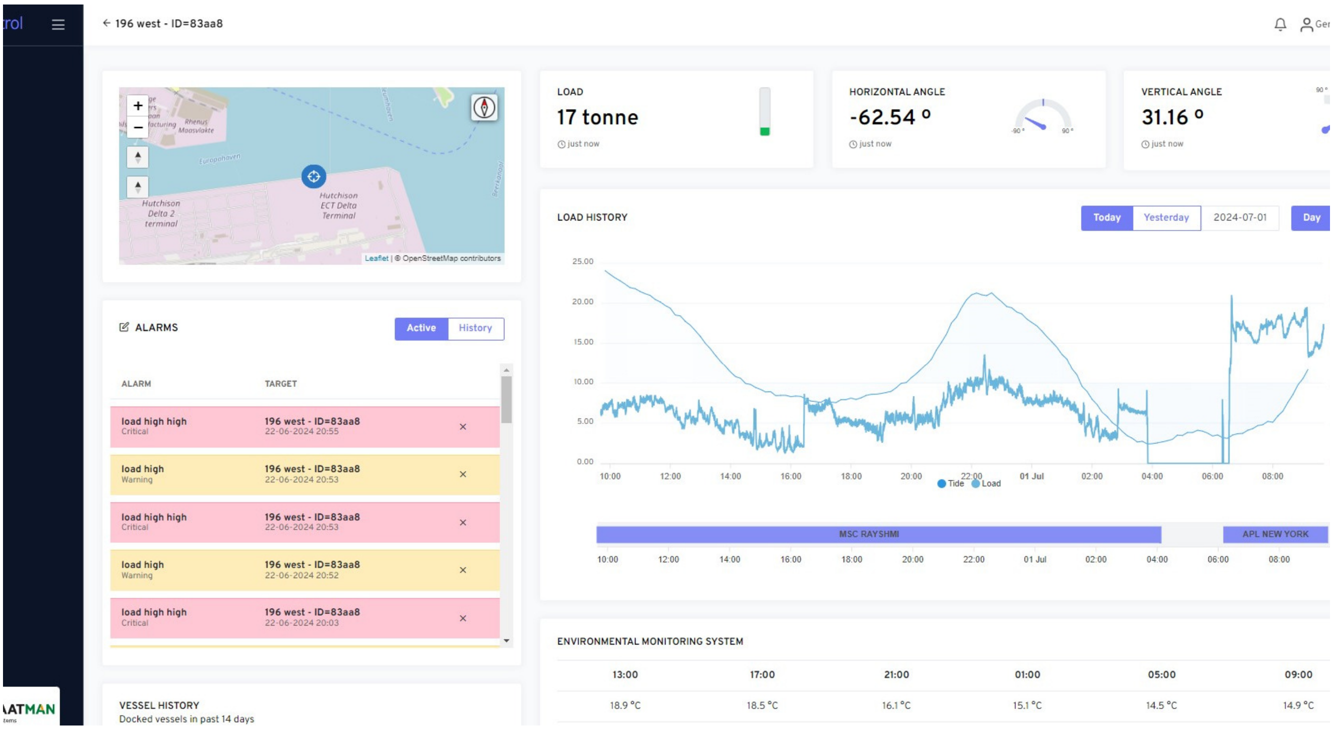

Figure 8 Online dashboard

9. Summary of final report

9.1 Smart Bollard Design

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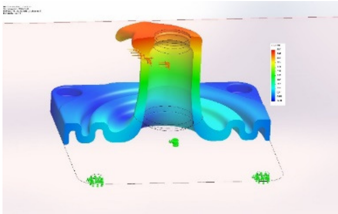

Figure 9 Smart Bollard drawing

9.2 Tests & Measurements

The Smart Bollard has been tested in a test bench and in practice. The practical tests were carried out with a load cell between the line and in a set-up with a test frame. The set-up with test frame gave the purest data and led to optimization of the formula/calculation.

In all tests there is a very strong linear relationship between force on the bollard and the measured/displayed reading. Various tests have shown that the Smart Bollard can measure reliably. The measured values are even more accurate than previously assumed.

The measurements with the Smart bollard have been adequately tested. Findings are as follows:

1) Load measurements are very accurate: Up to +/- 1 Ton accuracy possible in range from 0 – 120T
2) Measurements of direction horizontally are good: Up to +/- 10 degrees accuracy
3) Measurements of direction vertically are good: Up to +/- 20 degrees accuracy possible.

9.3 Design Adjustments

During the pilot and various tests , a number of findings led to adjustments to the design:

1) Keep pot holes sufficiently wide (hydraulic tools should fit easily)
2) No paint in place of nut -> is recommended by Hytorc)
3) Tape the shaft so that the line creeps up (see images)
4) Shaft diameter has been reduced compared to standard bollard due to adjustment of tapering of shaft
5) Development of the 300T version including modification of the footplate for integration into the Amaliahaven project

9.4 Conclusion

- ➔ With the right formula, very high accuracy can be achieved (+/- 1 ton). Expectation of maximum deviation of +/-5% expected in practice
- ➔ On-site measurements with test frame very valuable
- ➔ Operation of Smart Bollard has been proven
- ➔ Lines sometimes placed halfway on bollard, causing measured values to deviate. Modification to design can prevent this
- ➔ External factors such as sun/heat do not have a negative impact on the readings
- ➔ Determine ideal formula per type of bollard necessary, then no longer necessary per individual bollard

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