The Effects of Wave Loading on Sandbag Dike Stability

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ABSTRACT
This paper discusses research carried out to examine the effects of wave action on the stability of sandbag dikes used for temporary flood protection. The research involved the construction, instrumentation and wave loading of full-scale five-foot sandbag dikes. The testing was carried out in the wave flume in the Hydraulics Research and Testing Facility at the University of Manitoba. The test dikes were loaded using waves, generated with different wave heights, to determine their effect on the stability of the dike. The goal of this research is to provide insight into the strength and stability properties of sandbag dikes and to assist in the creation of policies for improved flood protection and public safety.

RÉSUMÉ
Ce papier examine la recherche faite sur l'effet de l'action d'une vague sur la stabilité d'une digue faite en sac de sable utilisée pour la prévention temporaire d'inondation. Cette recherche inclut la construction, l'instrumentation et le chargement de la vague à échelle complète sur des digues à une hauteur de cinq pieds. Ces épreuves ont eu lieu dans la flume à vague dans l'édifice de recherche et d'expérimentation hydraulique à l'université du Manitoba. Les digues mises à l'épreuve ont été chargées en utilisant des vagues produites avec hauteurs variées afin de déterminer leur effet sur la stabilité de la digue. Le but de cette recherche est de fournir des éclaircissements sur les propriétés de la force et la stabilité des digues construites en sac de sable et d'assister dans la création de ligne de conduite politique en vue d'améliorer la protection contre les inondations et ainsi améliorer la sécurité publique.

1 INTRODUCTION

Communities along the Red River in Manitoba have a history of flooding and continue to experience major flood events on a regular basis. Sandbag dikes have been used and continue to be used as a temporary flood protection measure when flood levels surpass the capacity of the permanent flood protection infrastructures. Sandbag structures protect millions of dollars of infrastructure as well as public safety and have performed with varying success throughout the history of their use. While these structures continue to be used, only recently has research been undertaken to gain an understanding of their engineering properties and behaviour (Krahn 2005).

Research into sandbag dikes began following the historic flood of 1997, where Manitoba experienced a 90-year flood event. During this flood the Red River which is normally about 150 m across, grew to a lake approximately 65 km wide and 100 km long (CBC 2008). Sandbags were used to erect temporary dikes to protect communities from flooding. As an example of the magnitude of their use, Winnipeg, the largest of Manitoba's communities, used 8 million sandbags to protect the city in 1997. In some parts of Manitoba, sandbag dikes encircled entire properties creating sandbag protected island within the flooded prairies. The dikes throughout the province performed with varying levels of success, however, little was known as to how these structures performed. The degree of which sandbags were used in 1997 demonstrated the need for an understanding of the engineering behaviour of sandbag dikes and led to several research projects. One of the research projects investigated the effects of wave action on the stability of sandbag dikes.

Wave action and its effect on permanent structures is a well established practice which has long been used in the design of permanent dikes throughout coastal regions of the world. Wave action on temporary sandbag dikes, however, is a unique study that had not been explored in detail. In Manitoba, during flood events, waves are generated in the flooded prairies or along reaches of the swollen rivers. The height and frequency of these waves depends on the speed of the wind travelling over some distance, or fetch length across the open water. This process is significant when you consider the extent of flooded land experienced in 1997. A research program, conducted at the University of Manitoba, was undertaken to develop an understanding of the effect of these waves on sandbag dikes. To achieve this goal, five-foot sandbag dikes were built within a hydraulic wave flume, instrumented and loaded with waves having different significant wave heights. This paper discusses the results of this research and provides insight into the mechanisms that lead to dike instabilities in the presence of waves.

2 WAVE APPARATUS AND DIKE CONSTRUCTION

The wave tests were run in a hydraulic flume located in the Hydraulic Research and Testing Facility at the University of Manitoba. The flume is 30 m long, 1.5 m wide, and 1.5 m high. The waves are generated within the flume by a wave board connected to a 40 hp hydraulic pump located at one end of the flume. The amplitude and period of the waves produced is controlled by the rate and distance that the wave board drives into the water within the tank. These movements are controlled by the software Wavegen, developed specifically for the flume. The software is designed for normal use of the hydraulic flume, where a sand beach is located at the opposite end of the flume to absorb the energy of the waves. During wave testing, the sand beach was removed and replaced with a sandbag dike. The dike had a sloped face of 1H:2V which changed the manner in which generated waves performed. The result was larger actual wave heights than the heights inputted to the software. To deal with this issue, calibration tests were carried out where waves were sent to the wave board and the actual wave train was measured with a wave sensor. The sensor used was a 1.254 m RBR WG-50 capacitance wave sensor. The sensor read the water level 100 times per second providing a continuous wave record. The wave record was then analysed using the zero up-cross method providing the measured significant wave height (Hs) for a specified file crated in Wavegen. During the calibration process, 30 different wave files were run, measured and analysed according to this method providing a list of significant wave heights that could be generated within the flume in the presence of a 1H:2V sloped sandbag dike.

2.1 Materials

Two basic materials were used during wave testing, Filled sandbags and polyethylene sheeting.

2.1.1 Sandbags

The sandbags used during testing were woven slit film polypropylene (WSFPP) bags. The WSFPP bags were provided directly from the City of Winnipeg stockpile of sandbags used for flood protection. The sand contained within the bags was tested and classified as SP (poorly graded sand) according to the Unified Soil Classification System and has a D_{85} = 3.48 mm, D_{50} = 0.66 mm, a uniformity coefficient (UC) = 3.71, and a coefficient of concavity (CC) = 0.72.

2.1.2 Polyethylene Sheeting

The test dikes used a 6 mil polyethylene sheet as a waterproof membrane. The PES is 3 m wide and is placed below the outermost bags on the wet side of the dike

2.2 Dike Construction

Each wave test involved the construction of a new 5 ft (1.524 m) sandbag dike in the wave flume, built in general accordance to the City of Winnipeg template for dike construction. The dikes were built with a width of 2 ft (0.61m) at the crest and 7 ft (2.13 m) at the base, supporting a water level of 3 ft (0.91 m) as shown in Figure 1. During construction, each layer of WSFPP bags was laid down perpendicular to the long axis of the flume (direction of the waves). The length of the dike was limited by the flume width. Given the average length of the filled bags, this length consisted of four bags laid down per row. Each bag, after being laid down, was tamped in place by foot. Every second layer of sandbags was setback by one quarter of a bag width on the dry and wet sides of the dike producing a step-like appearance. Figure 2 depicts a standard dike as constructed before testing.

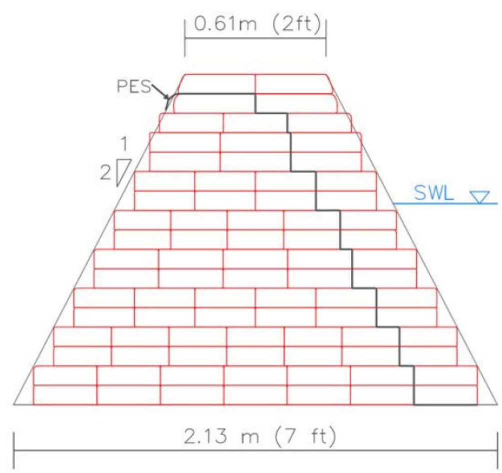

Figure 1. Typical dike cross section

Figure 2. Dike constructed in flume before testing.

3 INSTRUMENTATION AND MEASURING DEVICES

Investigation into the effects of wave action on hydraulic structures comprised of individual building units such as sandbags revealed that a likely failure mechanism would be the slippage of sandbags along the front (wet) face. An instrumentation and measurement program was established to capture these front face movements as well as the general stability of the dike. The following subsections describe the instrumentation devices and measurement methods employed during the research program.

3.1 Extensometers

Sixteen pull wire extensometers were used to track movements of bags during the tests. The extensometers were placed at four heights within the dike, two below the static water level and two in the freeboard region. Two models of potentiometer type pull-wire extensometers were used, the WPS-MK30-P and the WS42C. These sensors are spring loaded and provide voltage readings corresponding to the length of wire pulled from or released into the sensor.

3.2 Dynamic Piezometers

Twelve dynamic piezometers were installed into the dikes to measure the changes in pressure resulting from the wave action on the dike. These sensors were placed along the base of the dike to capture fluctuations in the piezometric surface as well as along the front face of the dike to pick up pressure changes that may result in bag movements. The sensors used were Geokon 3400 piezometers. They are semiconductor strain gauge piezometers capable of dynamically reading pressure changes between 0 and 100 kPa. The sensors are encased in 32 mm (1¼") diameter stainless steel tubes and were installed in the dike by placing them between the sandbags at the specified locations and running the wires up above the dike to the Data acquisition (D/A) system.

3.3 Data Acquisition (D/A) System

The extensometer and Piezometer data were collected using a Campbell Scientific CR23-X D/A system in conjunction with a Campbell Scientific AM 416 relay multiplexer. The piezometers were wired directly to the D/A for instantaneous readings when prompted whereas the extensometers were connected to the D/A via the multiplexer providing relative readings when prompted. Two programs were written using PC208W software to collect data during each test. The first program referred to as the "slow program" took piezometer and extensometers readings every 15 seconds. This program was run at the start of each test while the water level in the hydraulic flume was being raised to the static water level required for testing. The second program, referred to as the "fast program" read the extensometers every 15 seconds and the piezometers every 1 second. The fast program was run when the waves were initiated and ran for the duration of the test. The one second interval was selected for rate of reading the piezometer data to capture the general pressure effects of the waves and was less than or equal to the periods of the waves generated during testing.

3.4 Survey Measurements

Total station surveys were carried out to record the cross section of the dike before and after each wave test. To allow for comparisons to be made between the two surveys, "X" marks were drawn on the top of exposed bags along the centre of the dike. Only approximately half of the bags were surveyed due to the building technique of setting back every second layer of bags.

Laboratory personnel would stand on a timber bridge laid across the flume and use a modified prism pole to capture the data, to avoid affecting the dike's form during the survey. The prism pole was modified using a clear block of acrylic with an "X" mark below it, to avoid the pointed end of the rod from piercing the bags and maintaining a consistent mode of recording elevation. When collecting data points, the X mark at the base of the rod was aligned with the X mark on the top of the bags.

3.5 Front Face Bag Measurements

Front face bag measurements were carried out to provide relative horizontal displacements of each bag along the front face of the dike as measured before and after each wave test. The purpose of these measurements was to capture movements resulting from slippage of bags affected by wave loading on the wet face of the dike. To capture these movements, a plumb line was drawn on the wall of the flume and the distance to each bag was recorded.

3.6 Photographs and Time Lapse Video

Photographs and time lapse video were used to provide a visual record and qualitative results of each test. Photographs of the dike were taken from three specific locations prior to filling and following drainage of the hydraulic flume for each test providing snapshot comparisons of the effect of the different wave heights on the test dikes. A time lapse recorder was mounted above the test dikes and recorded a half second every minute for the duration of the test. The time lapse videos provided a visual timeline for movements, failures and/or full breaches of the dike during each wave test.

4 TEST SCHEDULE

The test schedule was dictated by the results of each test following the observational approach. As such, a detailed test matrix was not produced at the start of the testing program. Instead, a particular wave file was tested and the resulting data were analysed following the test. Tests continued while changing the significant wave heights until results had been produced that showed a range of dike stability from "no change" to "dike failure". The convention for dike failure used throughout this research refers to individual bag movements of 30 mm or more. The rationale behind this decision is significant and is based on observational data from full-scale dikes. Displacements of 30 mm at each layer in the dike resulted in excessive leakage and structural distortions that produced a breach of the dike (Krahn et al. 2007).

5 ANALYSIS

Instrumentation and measuring process all demonstrated that the wet face of the dikes tested became unstable as wave heights were increased. For the purpose of this paper, only selected figures and summary plots will be shown. The data in its entirety is available on-line at http://mspace.lib.umanitoba.ca/dspace/handle/1993/3151 as part of the thesis Wave Action and the Effects of the Environment on Sandbag Dike Performance (Offman 2009).

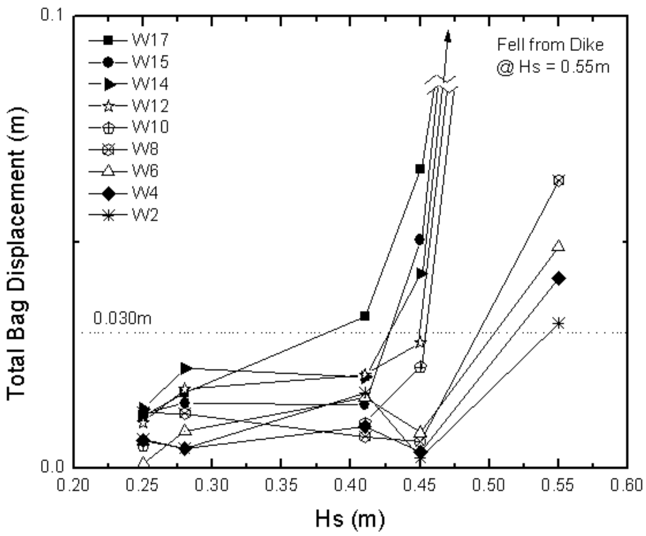

Figure 3. Change in wet face bag movement Vs. Hs.

Analysis of the instrumentation and measurement data and observations made during testing and from viewing the time lapse video's show that the dike became unstable when loaded with waves having a significant wave height in the range of 0.41 m to 0.45 m. Figure 3 plots the change in the pre- and post-test survey measurements of the wet face bags versus the significant wave height tested. This plot shows the bag displacements exceeded the failure criteria in the range of significant wave heights listed above. Figures 4 to 6 are photographs taken after testing for the dikes loaded with waves having significant wave heights of 0.25 m , 0.45 m, and 0.55 m, respectively. These photographs provide evidence of the risk associated with wave loading on sandbag structures. The dikes loaded with significant wave heights at or above 0.45 resulted in loss of bags and a significant reduction in dike height along the wet face of the dike. The dike exposed to waves of Hs = 0.55 m resulted in the entire loss of the front face of the dike.

Figure 4. Dike loaded with Hs = 0.25 m (end of test).

Figure 5. Dike loaded with Hs = 0.45 m (end of test).

Figure 6. Dike loaded with Hs = 0.55 m (end of test).

The most significant cause of the instabilities was the pressure changes along the front face resulting from wave loading. The effect of incoming and retreating waves produced a pressure change along the front face of the dike. This change in pressure led to sandbags being pulled away from the dike. More specifically, as one wave recedes from the dike, the pressure head is reduced and there is a downward seepage through the sandbags on the front face of the dike; A moment later, the next wave hits the dike resulting in a high pressure under the point of maximum rundown leading to upward flow through the sandbag. This interaction results in outward flow and uplift pressure (Pilarczyk et al. 1998). This theory was captured by the dynamic piezometers placed along the front face of the dike. Two separate piezometers were installed adjacent to each other to further capture the pressure change felt by a single sandbag. One measured the pressure along the outer face of the dike while the other measured the pressure just behind bag. Figure 7 shows a segment of the difference in these pressure readings plotted versus time for the highest and lowest wave heights tested. As expected, the plot shows that an individual sandbag experiences a regular cycle of both positive and negative pressures as the waves hit the dike. These cyclic pressure changes provided an additional source of instabilities whereby the sand within the bags was pulled through the woven material. This process was discovered through observations made during testing where a sand plume was observed emerging from the front face of the dike. The dynamic pressure change on the sand particles reduced the capability of the sandbag to retain soil particles. Cyclic retention calculations were carried out on the sandbag which recommended an apparent opening size (AOS) ≤ 1.74 mm. The WSFPP bags used during the testing have an AOS = 0.375 mm which should be acceptable, however there is a flaw in this assumption. During AOS testing the material being tested is pulled tight, which is counter to the purpose of the wave experiments, where the bags are free to flex in the presence of the waves. As the bags flex, the woven fibres may be pulled apart increasing the AOS and allowing additional sediment to be lost. This loss of particles leads to a reduction in the bag volume providing a greater potential for the bag to become dislodged from the dike due to the pressure effects of the waves.

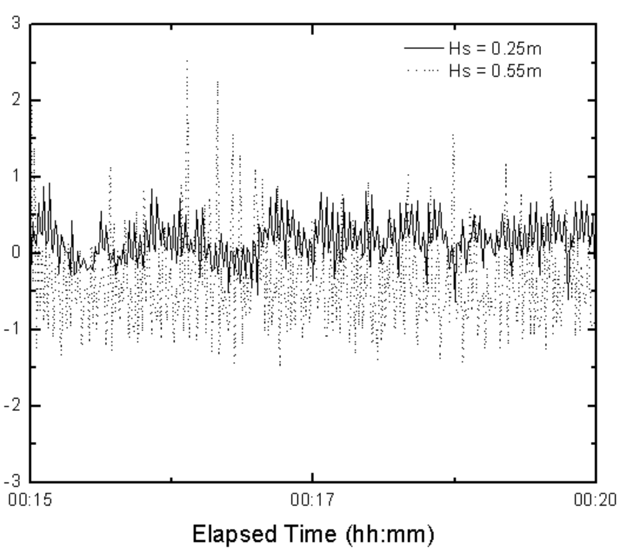

Figure 7.Pressure change across a single bag

To further explore this concept, a single test was devised, where the sandbags along the wet face of the dike were replaced with non-woven geotextile bags having a nearly identical AOS (0.300 mm). This dike (figure 8) was loaded with a significant wave height of 0.41 m, the same wave height that had caused instabilities when loaded on a dike built entirely out of the woven slit film polypropylene bags. The results of this test was that the test dike built with non-woven geotextile bags on the front face underwent smaller displacements than the standard dike tested with the same wave height. It is difficult to make a direct comparison as to a level of improvement that was observed, since the shape, weight and material of the non-woven bags were all changed from the standard test. The test simply provides insight into the potential of using non-woven bags as an alternative along the front face of a dike exposed to wave action.

Figure 8. Dike tested with non-woven sandbags.

6 CONCLUSIONS

The wave tests described in this paper demonstrated that a five-foot high dike built according to the City of Winnipeg template for dike construction became unstable when loaded with a significant wave height in the range of 0.41 m to 0.45 m. This research demonstrated the risks associated with wave action on sandbag structures and provided insight into the engineering mechanisms that lead to instabilities caused by wave loading. The research also proposed a new sandbag material to increase sandbag dike stability against wave action. This research is part of a greater study into understanding the overall behaviour of sandbag dikes that are regularly used to protect communities throughout Manitoba during flood events. This Study will be used by both the Province of Manitoba and the City of Winnipeg to create policies that will improve the protection of public safety and infrastructure.

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