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11 Validating models in the face of uncertainty

Geotechnical engineering and dike vulnerability in the Netherlands

Matthijs Kouw

Introduction

The geographical position of the Netherlands makes it crucial to assess the safety of Dutch flood defenses. About 3.4 million Dutch (21 percent of the total population) live below sea level (Centraal Bureau voor de Statistiek 2008: 65). Nineteen percent of the gross national product (GNP) is earned below sea level, although a total of 32 percent of GNP is earned in areas that are prone to flooding (Centraal Bureau voor de Statistiek 2008: 64). Geotechnical engineering, a subdiscipline of civil engineering concerned with the behavior of soil under different conditions, fulfills a crucial function in this regard by modeling processes that cause flood defenses (e.g. dikes, dams, and sluices) to fail. Such processes are also known as failure mechanisms. Geotechnical modeling relies heavily on both physical models (e.g. scale models of flood defenses that are subjected to water pressures) and computational models (e.g. calculation rules that simulate the relationships between soil morphology and structural stability). Geotechnical models need to be validated to determine their ability to provide an accurate and reliable assessment of the safety of flood defenses.

As various studies of modeling practices have shown, pragmatic and contextual considerations shape model validation (e.g. Morgan and Morrison 1999; Oreskes et al. 1994; Winsberg 2006). Morgan and Morrison (1999) argue that modeling should not be interpreted exclusively in terms of mirroring or mimesis of target systems, but also with close attention to the demands of particular settings: "[W]e do not assess each model based on its ability to accurately mirror a system, rather the legitimacy of each different representation is a function of the model's performance in specific contexts" (Morgan and Morrison 1999: 28). Thus, the performance of models can be assessed in terms of "relevance" rather than truth. In this perspective, social groups attribute explanatory power and reliability to models by virtue of the latter's contribution to solve a particular problem, making the models in question relevant for these social groups.

Drawing on insights from Science and Technology Studies (STS) and an ethnographic study of geotechnical engineering conducted at Deltares (a Dutch institute for applied research on water, subsurface and infrastructure) between 2009 and 2011, this chapter examines modeling practices and the validation of models pertaining to research on a dike failure mechanism known as "piping."

which is a form of seepage erosion. Calculation rules and models of piping serve to predict the risk of dike failure. Piping research and modeling may be regarded a specific case of a culture of prediction in geotechnical engineering. As will become clear, research on piping features a series of steps and model-related forms of knowledge production, where each step produces knowledge that is made available for subsequent steps. Of particular importance are the development and adoption of computational models.

Over the course of the twentieth century, geotechnical engineering has come to rely more heavily on computational models (i.e. models based on mathematical insights that require computational resources to run simulations of complex systems). This trend can be attributed to water management across the board (Kouw 2016). Disco and van den Ende (2003) explain the widespread adoption of computational models by pointing out that such models fulfilled a crucial role as management tools in Dutch water management, and met a more general desire to quantify water-related phenomena. The successful application of computational models implies "black-boxing" (Latour 1987, 1999): "When a machine runs efficiently [...] one need focus only on its inputs and outputs and not on its internal complexity. Thus, paradoxically, the more science and technology succeed, the more opaque and obscure they become" (Latour 1999: 304). The successful application of black-boxed technologies, in this case computational models, means they are taken for granted and only come into view when failure or malfunctioning renders them obtrusive.

Uncertainty features prominently in all steps of the modeling chain deployed in the case of piping. Uncertainty is sometimes defined as a lack of knowledge (Petersen 2012; Kouw et al. 2013). I adopt Gross' (2010) definition of uncertainty as "a situation in which, given current knowledge, there are multiple possible future outcomes" (Gross 2010: 3). Uncertainty can produce new insights about risks: "multiple possible future outcomes" might produce insights about risks and what to do about them. Various forms of uncertainty emerge in geotechnical modeling, and social groups deal with these uncertainties in diverging ways. The use of geotechnical models in the laboratory can serve to investigate uncertainties of geotechnical phenomena and to acquire a deeper understanding of these phenomena. Outside of the laboratory, users of geotechnical models may be less inclined to study the uncertainties of geotechnical phenomena. In this regard, black-boxed technologies can travel easily from the laboratory to contexts outside of the laboratory (e.g. decision making and policy making). When accepted without further questioning, black-boxed geotechnical models may cause users of such models to gloss over uncertainties. Black-boxing geotechnical models, hence, is a powerful way of domesticating uncertainty and making it largely invisible to its users. This paper shows how black-boxing occurs in various steps of piping-related modeling, and argues that black-boxing may not bode well for the potential of uncertainty to function as a source of knowledge, which may negatively impact the safety of the Netherlands.

The main questions of this chapter are as follows: how do geotechnical models contribute to the production of knowledge about dike failure mechanisms

that is considered relevant by the social groups involved, and how may the various ways in which these social groups deal with the uncertainties involved with the use of geotechnical models put the Netherlands at risk? I address these questions by first describing how geotechnical engineers deploy modeling in their study of piping. Subsequently, I describe how knowledge thus developed is used in social domains outside of geotechnical engineering. In both cases I address the black-boxing of knowledge, what knowledge is considered relevant for the social groups involved, and how uncertainties that arise are addressed.

Piping

Piping is a form of seepage erosion involving the movement of water under or through a dike that provokes instability, in some cases leading to dike breaches and even dike failure. High water levels lead to high water pressure or "hydraulic head" on the water side of the dike, which may cause a flow of water under or through a dike. This flow can build channels or "pipes," which eventually form a shortcut between the two sides of the dike and run through the dike and/or its foundations. In such cases, water wells up through soil (also known as a "sand boil"), which is an important visual indication that piping is in progress. Shortcuts between the dike's water and land sides transport large amounts of soil and dramatically increase the speed of erosion, which may damage the dike or its foundations to such an extent that the dike collapses or breaches. In the Netherlands, many dikes consist of clay and/or peat that sit on foundations of sand, particularly in the vicinity of the main rivers of the Netherlands. Since clay and peat are cohesive and relatively impermeable while sand is relatively permeable, many dikes in the Netherlands are prone to seepage erosion of their foundations.

The composition of dikes and their foundations, and the interactions between different types of soil in dikes and their foundations, are sources of uncertainty in geotechnical engineering. The composition of soil may be known at locations where measurements have been taken, but soil can be rather heterogeneous, implying major differences between measuring points. In addition, geotechnical engineers stress the difficulties imposed by the complexity of interactions between different kinds of soil. Such interactions are not understood very well yet, and remain a source of uncertainty.

To gain an understanding of the behavior of soil, geotechnical engineers rely heavily on experiential knowledge. There are only a few detailed observational accounts of the piping process. More importantly, most of the piping process is inaccessible to the human senses, since it takes place inside a dike. Today, physical and computational models provide important extensions of the human senses, allowing geotechnical engineers to study phenomena otherwise inaccessible to them. Physical models of dike foundations on different scales provide the means to study the conditions that provoke piping, how piping proceeds, and what conditions influence the onset and progress of piping, for example, the composition of the dike's foundations and the hydraulic head.

Differences in the shape and size of grains of sand make for different types of sand, which also behave differently under pressure. To acquire an understanding of piping, qualitative physical experiments are carried out using a cross section of the foundations of a hypothetical dike. A Plexiglas window covers the cross section so that the process of piping can be observed. Water pressure is applied on one side of the cross section to simulate the hydraulic head that provokes the onset of piping. A part of the cross section is covered with a counterweight to simulate the pressure exerted by the top layer of the dike. Part of the cross section on the right-hand side is left open to simulate the presence of a ditch, which can offer a way for the water to come to the surface due to the water pressure exerted by the hydraulic head.

Based on empirical observations acquired during physical experiments, calculation rules can be devised and validated. An example of such calculation rules can be found already in the early twentieth century, when the British Colonel Bligh concluded that the loss of hydraulic head is proportional to the distance water travels (also known as creep length). Increasing creep length can be an important way to decrease the risk of seepage erosion (Bligh 1910). Similarly, calculation rules pertaining to piping describe relationships between hydraulic head, soil properties, and creep length.

Calculation rules are needed to develop computational models of piping and once formalization in the form of calculation rules is possible, it is possible to develop computational models that run simulations based on these calculation rules. In this regard, it is possible in principle to develop quantitative approaches to geotechnical phenomena. Formalization in the form of calculation rules in combination with quantitative measurement of certain phenomena relevant to piping (e.g. hydraulic head, creep length) allows the risk of piping to be predicted. In the following, I refer to this combination of calculation rules and measurement as quantitative methods. However, calculation rules currently do not fully describe and predict piping, making it necessary to introduce empirical parameters based on physical experiments.

Earlier physical experiments in the 1990s were not carried out to the point where a "full" pipe acted as a shortcut between the water and land side of the dike, since this would have damaged the experimental setup (Vrijling et al. 2010: 41). As a result, the hydraulic head that would provoke "retrograde erosion," where a pipe forms a shortcut between the dike's water and land sides, was not determined. A further shortcoming of these earlier experiments on piping is that the highly influential morphological properties of soil were not studied exhaustively. The critical head is influenced by the thickness of the sand layer and top layer in question, the permeability of the sand layer, and soil morphology (e.g. size and shape of sand grains). Despite these interacting complexities, initial calculation rules developed to calculate critical head assumed the homogeneity of soil.

Piping found its way back to the research agenda of Deltares in 2007. An important influence in this was the *Veiligheid Nederland in Kaart* (VNK or Mapping the Safety of the Netherlands) effort, a collaboration between the Dutch Ministry of Infrastructure and the Environment, the water boards of the Netherlands,[1] and the Interprovinciaal Overleg (a foundation comprising the provinces of the Netherlands as members). The first phase of VNK took place between 2001 and 2005, and concluded that piping posed a substantial risk to dike safety in the Netherlands (Rijkswaterstaat 2005: 90). The calculations used in VNK are based on scenarios that include extreme water levels that have never been observed. However, these hypothetical water levels had very concrete repercussions. During the first phase of VNK, the shortcomings of calculation rules developed in the 1990s became the subject of debate (Vrijling et al. 2004). When the use of these calculation rules led to high estimations of dike failure due to piping, the various parties involved with VNK found it necessary to improve the accuracy and reliability of these calculation rules. As a result, a new round of research on piping commenced in 2007.

Small, medium, and full-scale physical experiments

Experiments similar to those in the 1990s were carried out using small-scale (see Figure 11.1) and medium-scale physical models. An important motivation behind these experiments was the desire to acquire observational knowledge of the piping process.

When I attended a physical experiment using a medium-scale physical model, I was introduced to some of the challenges related to the study of piping. During the experiment, the model was covered with a thick sheet of black plastic to keep sunlight out and minimize reflections on the Plexiglas sheet that covered the layer of sand that was studied. Light and reflections can compromise the quality of the camera recordings used to capture the process of piping. The lamps used to illuminate the experiment generated heat, introducing discomfort on the part of the scientists, for whom tracing the movements of individual grains of sand required utmost concentration. More than once, a moving grain of sand was a source of modest celebration or at least a welcome change in an otherwise fairly uneventful experiment. The experimenters concentrated on the movement of individual particles, and studied how the meandering flows of water created small channels that would sometimes persist, but could also disappear quickly. When the experiment was not very eventful, the water pressure that simulated the hydraulic head would be increased. This was usually not done according to an exact and elaborate protocol, but rather to provoke some kind of worthwhile event, for example, moving grains of sand or the buildup of meandering channels.

The use of geotechnical models on a scale smaller than the target systems in question leads to different behavior of soil (e.g. due to different effects of gravity). As a result, some phenomena observed in a physical model may occur only in the laboratory, and may therefore not be representative of their target systems. To provide more elaborate means of studying piping and the calibration and validation of geotechnical models, geotechnical engineers have

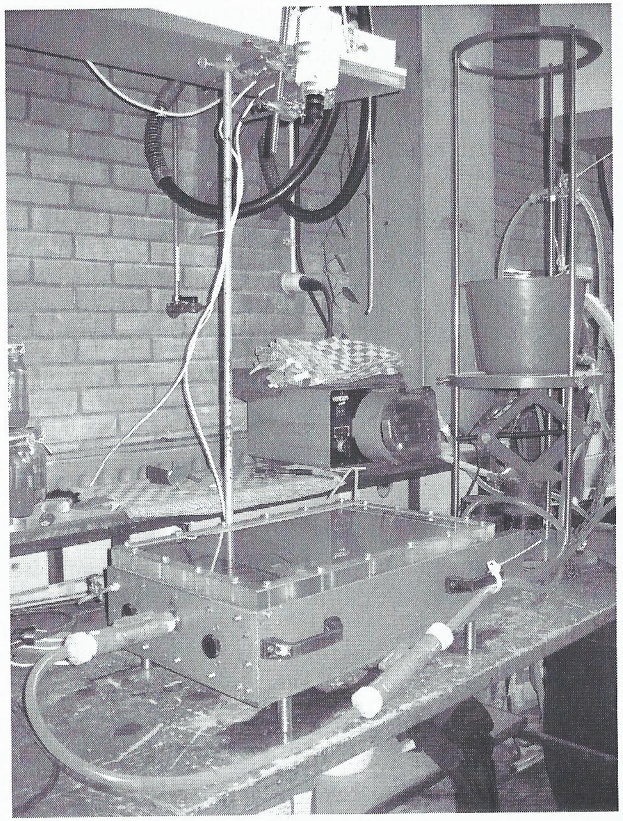

Figure 11.1 Physical model used for small-scale piping experiments. Water is forced to flow from the bucket on the right hand side through the cross-section of a dike underneath the Plexiglas window. Increasing the bucket's height simulates a greater level of hydraulic head.

Source: Photo by Vera van Beek, courtesy of Deltares.

conducted physical experiments using full-scale dikes as part of the so-called 'IJkdijk' (literally 'calibration dike') program (see Figure 11.2).

The IJkdijk experiments provided additional insights into the onset and progress of piping. A total of four experiments related to piping were conducted at the time of writing, in all cases leading to dike failure, proving once and for all that piping needs to be taken seriously. According to the engineer leading Deltares' piping research, this result was expected by the geotechnical engineers involved. However, several water boards were not convinced piping was really an issue until the IJkdijk experiments (interview, 27 May 2009). The IJkdijk program, therefore, had an important persuasive effect as well.

Figure 11.2 An IJkdijk after an experiment in late 2009.

Source: Photo by Vera van Beek, courtesy of Deltares.

The ensemble of small, medium, and large-scale physical models used by geotechnical engineers helped to address the complexities of soil morphologies and the uncertainties introduced by modeling geotechnical phenomena on different scales. When IJkdijk experiments validate the outcomes of smaller-scale physical models, the latter are considered more reliable. This reduces the necessity of conducting expensive physical experiments on a full scale, and allows smaller-scale experiments to be conducted with more confidence. An important outcome of the small and medium-scale physical models in combination with the IJkdijk experiments was the correction of existing calculation rules. These calculation rules did not predict critical head correctly in the case of coarse sand particles. A further result of the IJkdijk experiments was that geotechnical engineers learned more about the time it takes for a dike to fail because of piping. For example, retrograde erosion turned out to take much longer than expected. Small-scale physical models usually showed a single channel where the process of retrograde erosion proceeded quickly. In large-scale physical models, the process of retrograde erosion could occur suddenly and violently, but could also take several days.

Relevant knowledge and uncertainties in geotechnical research on piping

Although much progress has been made in terms of validating existing calculation rules used to assess piping-related risks, the research is not complete.

In fact, geotechnical engineers question the ability of calculation rules to provide robust predictions, as not all aspects of piping are understood and represented sufficiently. One geotechnical engineer involved with the modeling of piping put it as follows:

> A risk with large-scale physical experiments is that you try to validate too many things, and that is not possible. So the setup has been relatively simple, as were the aims of the model validation. But you cannot validate all of the aspects of the model. Eventually you will get a critical head in the form of a number, and the only thing you can do is check whether that number corresponds with what we thought, and yes, on that basis you need to trust the model, but you cannot validate all aspects. That is tricky. That requires many more experiments.
>
> (interview, 24 June 2011)

Despite these shortcomings, Rijkswaterstaat (an organization that is part of the Dutch Ministry of Infrastructure and the Environment and is responsible for designing, constructing, managing, and maintaining the main infrastructure facilities in the Netherlands) considered the process of validation that was carried out as sufficiently thorough. However, the head of piping research at Deltares points out that additional physical experiments are needed as a basis for comparing the outcomes of different runs of computational models:

> The research does not rid you of the problem of deducing simple calculation rules. You keep discovering new blind spots. The moment you have a calculation rule, it may be state of the art, but that does not mean you are really at the end of the research [...] one experiment is no experiment, you always need to compare the results of different experiments, but it is always a question of time and money [...] *Rijkswaterstaat* expects us to come with a new calculation rule this year, so there comes a point where you have to say good is good enough. But uncertainties remain.
>
> (interview, 27 May 2009)

The head of piping research at Deltares further explains that the outcome of piping-related modeling can be counterproductive in terms of reducing uncertainties in calculation rules. More knowledge about piping can also lead to the realization that more uncertainties apply to piping, which may unsettle the credibility of calculation rules previously deemed trustworthy. For example, the shape of sand grains may turn out to be a complicating factor, which would give rise to the need to incorporate details on sand granularity in calculation rules. As a result, the head of piping research at Deltares argues, it may be unlikely that geotechnical phenomena can be captured once and for all in calculation rules due to the complexities pertaining to such phenomena (interview, 27 May 2009).

Another geotechnical engineer at Deltares working on piping expressed his doubts about attempts to capture piping once and for all in a calculation rule:

> I do not believe in a calculation rule that represents reality. The phenomenon features lots of different aspects, and you can never capture those correctly. You have to provide a schematization of reality before you can start calculating, and reality is so complicated. Those sand layers can be one centimeter thick, they can be small, large, vertical, and horizontal, making the soil so heterogeneous you cannot capture it in a single calculation rule.
>
> (interview, 26 May 2009)

The physical experiments in the laboratory provide ample evidence for this particular engineer's observation that piping is a rather complex and local phenomenon, in which the interactions of heterogeneous soil can have a crucial effect. In principle, vast quantities of information about soil could make a difference, but measuring soil in great detail introduces practical limitations (e.g. available resources, accessibility of measuring points). In addition, the onset and process of piping can be sudden, making even the hypothetical scenario of perfect computational models in combination with exhaustive data about soil problematic in terms of preventing piping altogether.

Other difficulties are related to experimental setups, which may introduce additional uncertainties. For example, geotechnical engineers need to find out what types of sand need to be used in the cross section of physical models, ensure the water pressures used correspond to the conditions of dikes in the Netherlands, and determine whether the Plexiglas cover exerts the right pressure on the model foundation. In the case of the IJkdijk program, producers of measuring devices and sensors were eager to fill the dikes used during IJkdijk experiments with measuring devices, which came to a point where the devices could influence the experiment, as they were located on the border between the sand layer and the clay of the dike. Further complications arose due to the use of generators near the area where the IJkdijk experiments took place—a remote site in the north of the Netherlands. These generators provided power necessary for lamps and other devices, but may also have influenced the experiment by generating vibrations that introduce noise measurements. However, it is not uncommon for such vibrations to occur in the case of a "real" dike whenever trucks or ships pass by.

By means of elaborate simulations with an ensemble of physical models, existing calculation rules used to assess piping-related risks are validated and improved where necessary. The use of geotechnical models in research on piping revealed sources of uncertainty that warrant further research, for example, the difficulties encountered in the laboratory, such as the challenges of understanding soil morphologies and difficulties associated with the experimental setting of geotechnical models. In addition, the issue of scaling may reduce the reliability of small- and medium-scale physical models. These aspects of piping need to be addressed by future research, which is dependent on the allocation of resources from parties like Rijkswaterstaat or companies that consider projects like the IJkdijk to be worthwhile. Geotechnical models need to perform within the specificities of geotechnical research relevant for dike safety policies by producing "deliverables," in this case state of the art calculation rules that are considered to be reliable not only by geotechnical engineers, but also by other social groups, including decision makers, policy makers, and stakeholders. In the following, I show how calculation rules become black-boxed in the form of software despite the previously mentioned uncertainties. This does not bode well for the ability of social groups outside the domain of geotechnical engineering to grasp the full scope and impact of uncertainties that arise with the use of geotechnical models to study piping.

From experimentation to data gathering

Within geotechnical engineering, models fulfill a primarily heuristic role by virtue of being representations "useful for guiding further study but not susceptible to proof" (Oreskes et al. 1994: 644). In other social domains that make use of geotechnical models, the latter fulfill the role of representations used for flood risk management, safety assessments, and dike safety policies. Thus, the role of geotechnical models cannot be framed exclusively in terms of their exploratory function. In this section, I elaborate on the representational role of geotechnical models in social domains outside of geotechnical engineering. The quantitative methods described in the previous section referred to calculation rules developed on the basis of empirical observations. Although such quantitative methods return in this section, I refer to "data-intensive" methods where I discuss quantitative methods that are augmented by large amounts of data and computational power. In this context, quantitative methods produce the perception that geotechnical models provide reliable explanations.

As I showed in more detail in the previous section, geotechnical engineers do not consider the availability of calculation rules as indicative of a complete understanding of piping. Still, physical models are often abandoned in favor of computational models. As the head of research on piping at Deltares put it:

> As soon as there is a degree of certainty about the process, physical models are supposedly no longer needed [...] I think you still need to look at physical models to get some kind of sense of phenomena. If you only work with computational models you might distance yourself too much from reality.
>
> (interview, 27 May 2009)

According to all the geotechnical engineers at Deltares I interviewed, validated geotechnical models are not really "true" in a literal sense. Rather, validated geotechnical models are true in a pragmatic sense and can be considered sufficiently reliable in terms of understanding and predicting piping. Many of the engineers

display a belief in "progressive understanding": At some point, calculation rules about piping are considered to be reliable, allowing the codification of knowledge in the form of a calculation rule, which allow quantitative methods that signal a departure from qualitative physical experiments in the laboratory.

The viability of data-intensive methods is based on the presumption of computational tractability—the ability to quantify phenomena and subsequently predict or monitor these phenomena using computational methods. However, social groups have differing commitments to computational tractability. Two engineers working at the Netherlands Organisation for Applied Scientific Research (TNO) that I interviewed argued that geotechnical modeling and data-intensive methods can be combined to create a novel approach to dike safety. For example, data about past events can be fed into a database, which can then be consulted to predict the likely behavior of a dike in those cases where present circumstances are similar to those in the past. One of the engineers explained this as follows:

> You do not have to understand geotechnical phenomena to be able to predict them [...] if you can analyze a large amount of data by means of Artificial Intelligence, you can make statements about the future without understanding the process [...] a dike watcher will do the very same on the basis of past experiences and common sense without having a clue about what goes on inside the dike.
>
> (interview, 30 July 2009)

Although dependent on the acquisition of data and the accuracy of data collected, data-intensive techniques can guide the attention of experts and can point out which dikes need to be subjected to further scrutiny, for example, by carrying out structural improvements or monitoring their status more closely. Calculation rules may pave the road for quantitative approaches that shift the focus of engineers away from physical experimentation, and justify an emphasis on monitoring techniques that focus on data generation and data management. Presentations on the value of monitoring techniques are usually combined with references to "innovative" technologies, such as laser imaging detection and ranging (LIDAR), which is used to detect dents in the surface of dikes that can indicate damage in its structural integrity; remote sensing, which can detect temperature differences that can indicate the permeation of water in a dike that might be caused by damage inside the dike; and the use of sensors to monitor temperature and humidity.

Despite these promising developments, quantitative techniques should be approached with caution. When measuring devices are too far apart, a pipe can simply disappear "under the radar" and remain unnoticed. A further problem is that it is unclear how long it takes for a dike to fail as a result of piping. Although computational models allow sophisticated calculations, they can also be used without understanding the underlying processes and the availability of sufficient data to validate the model in question. The complexity of soil morphology and the lack of data about soil problematize the validation of computational models. A strong reliance on such models can lead to wrong assessments, especially in the absence of data to validate the model. A university professor working at the Department of Earth Systems Analysis (ESA) at Technical University Twente further clarifies this potential problem:

> As long as you keep the shortcomings of models in mind, it is fine to rely on computational models. However, when the output of a geotechnical model is used in large-scale projects, things can go awfully wrong. Model output is often accepted as being holy without being subjected to further attention [...] if model output does not differ too much from reality, people simply carry on using computational models.
>
> (interview, 5 June 2009)

It is crucial that the inner workings of the model in question are understood, the university professor quoted above argues in more detail, because the process of validation may only generate more uncertainties. Understanding how computational models yield a particular result enables a degree of control, which can be used to critically assess their output.

Still, geotechnical engineers need to meet the demands of professional environments and the political arena, which often require them to produce quantitative knowledge. Expert judgments are no longer seen merely as a sufficient basis for making decisions in those environments, since they are not unanimously accepted and cannot be controlled easily. The use of data-intensive techniques provides Dutch water management with an innovative edge, and may seem to enable reliable approaches to flood risk management in the eyes of policy makers. In sum, there are different and not necessarily compatible commitments to the idea of computational tractability. Geotechnical engineers tend to interpret the output of physical and computational models as a result that needs to be revised constantly in the light of new research results. In the eyes of members of other social groups, such as decision makers, policymakers, and stakeholders, computational tractability is more likely to enable monitoring techniques that are valued as reliable, innovative, and cutting-edge.

Flood Control 2015

Codified calculation rules enable the dissemination and reproduction of geotechnical knowledge, which can travel outside of the laboratory to policy contexts in the form of software applications. The use of data-intensive methods further adds to the perceived credibility of such applications. Flood Control 2015, a consortium made up of commercial companies and governmental institutions (i.e. Arcadis, Deltares, Fugro, Royal Haskoning, HKV, IBM, ITC, Stichting IJkdijk, and TNO), aims to develop data-intensive applications for flood mitigation. These applications are in many cases aimed at decision makers, policy makers, and stakeholders, and are used for measuring, monitoring, forecasting, mitigation, and training. More generally, flood risk management increasingly embraces the process of translating expert knowledge to the operational contexts of decision makers, policy makers, and stakeholders, which is expected to lead to robust and participatory forms of flood risk management. The consortium produced a series of applications that raised significant interest in the world of flood risk management. These applications have been praised as innovative and cutting-edge technologies that translate geotechnical knowledge to a public of non-experts. The Flood Control 2015 project is emblematic of the shift to a more adaptive style of flood risk management, since it contains many projects that display a strong commitment to evacuation and the idea of "preparedness," which "proposes a mode of ordering the future that embraces uncertainty and 'imagines the unimaginable' rather than 'taming' dangerous irruptions through statistical probabilities" (Aradau 2010: 3). Forms of flood risk management that emphasize preparedness imply a new form of citizenship, in which commitments to self-sufficiency shift the responsibility of responding to critical events to citizens.

On 20 January 2010, the Flood Control 2015 consortium organized a symposium that functioned as a showcase of their various projects. Throughout the symposium, the free circulation of accurate information was stressed as a crucial component of successful adaptive strategies. The keynote lecture of the event featured a slide showing a conference room, dubbed the "war room," filled with men (with one single exception), laptops, and beamers projecting maps of the Netherlands and feeds of data related to flood risk and dike safety. Such war rooms can function as central nodes in networks of information that are of crucial important during a crisis, and allow water boards to successfully plan and execute the evacuation of a particular area. "In such situations," the lecturer pointed out, "it is quite pleasant when those present are primarily experts and not politicians." Laughter erupted from the room. Still, the need to bridge the gap between "experts" and "non-experts" was stressed again and again.

The idea of sharing information reverberated throughout the day, but was certainly not embraced unconditionally. A project that bears close semblance to the "war room" environments presented in the keynote lecture is the so-called "Demonstrator Flood Control Room" (DFCR), an interactive user environment that features a variety of applications that can be used to analyze and visualize data from flood and dike monitoring networks. The DFCR functions like a central control platform by integrating data feeds generated by other components of the Flood Control 2015 project, including the sensor networks and remote sensing technologies discussed earlier, which allow it to present weather conditions, water levels, and the status of dikes in a particular area. Although computational models are an important component of the DFCR, running those models often requires a tremendous amount of computational resources and therefore cannot always be applied in crisis scenarios. One possible remedy is to lower the resolution of computational models, dramatically decreasing the time needed to run them. Another solution is to run computational models beforehand using input data that corresponds with scenarios that have a high probability, and subsequently include the output of these model runs in the DFCR. In that case, calculations are not carried out during the actual use of the DFCR, making users reliant on model output rendered before the event of an actual critical situation. An additional use of the DFCR is as a training environment, since it can simulate different scenarios to which users need to respond.

Although participants of the symposium valued the DFCR as a platform to integrate information, its possible implementation was approached with caution. Using the DFCR as a central platform to share data among different parties might make the dissemination of data more efficient and reliable. However, the successful implementation of the DFCR depends on a process of standardization that that is problematic, since local requirements differ from the standards used in the DFCR. The discussion around standardization deals with such practical problems, but also turns to potential dangers—what if uncertainties and assumptions are hidden in the data, which reveal themselves only when it is too late? Black-boxed quantified information can travel more easily to different domains of use in principle, but does not appear to roam about freely. The solutions pertaining to the dissemination of information thus occasionally tend to emphasize technological possibilities rather than considerations related to actual applications.

A related example of applications used to disseminate knowledge from "experts" to "non-experts" is the game called "Levee Patroller" (see Figure 11.3), which was created by a team of software engineers at Deltares who specialize in the development of "serious games"—computer game environments developed for educational purposes.

The Levee Patroller game is currently used to train dike watchers and includes a representation of piping. The game deals with piping by including animations of sand boils (described in section "Piping") to address this failure

Figure 11.3 Screenshot from the "Levee Patroller" game showing a damaged dike.
Source: Courtesy of Deltares.

mechanism. The Levee Patroller emphasizes "procedural skills" rather than the "conceptual understanding" of piping on the part of its users (Harteveld 2011: 233). Players of the Levee Patroller game earn rewards by correctly identifying risks and subsequently reporting those risks to a water management authority. This may be a suitable way to make users of the Levee Patroller aware of the piping phenomenon in general. However, although sand boils indicate that piping is indeed in progress, they do not provide a clear indication of how much the process of retrograde erosion has advanced. What is more, the onset and process of piping can be both gradual and sudden. Once a sand boil is visible, one may already be too late.

A complication related to the dissemination and application of information is that expert knowledge from engineering environments needs to be translated to meet the demands of decision makers, policy makers, and stakeholders. Applications that fit these demands need to be designed, and imply both an enabling and constraining effect on the user's interactions (Akrich 1987). This requires an elaborate process of distilling large amounts of expert knowledge in such a manner that decision makers, policy makers, and stakeholders are presented with information that is considered to be sufficiently detailed for the issues they face in a time of crisis. However, underlying geotechnical models are effectively black-boxed and the technologies in question are presented as innovative and cutting-edge platforms to represent information gathered by means of data-intensive methods.

Organizational challenges also apply to flood risk management. During a session at the Flood Control 2015 event described earlier, participants were asked to enact an evacuation scenario. The session's organizers attempted to tackle the issues that come up during evacuations, especially in the negotiations between local authorities, such as decision makers, the police, and firefighters. The participants discussed whether a single actor should have a mandate that allows him or her to make swift decisions, and how the behavior of citizens and decision makers can be uncertain in times of crisis. Citizens may simply not respond to the request to leave their homes, and decision makers may not decide purely on the basis of information about a critical scenario, which is often already uncertain itself. Although evacuation plans and training for evacuation scenarios were seen in a positive light, participants also stressed the importance of deviating from such plans when necessary.

Relevant knowledge and uncertainties in data-intensive methods and the Flood Control 2015 project

The use of data-intensive methods not only opens up new ways of engaging geotechnical phenomena for engineers, but also facilitates the development of "smart" and "innovative" applications in the form of software, which are expected to enable adaptive forms of flood risk management. Data-intensive techniques provide an important platform for geotechnical engineers to secure resources for further research. Geotechnical engineers can mobilize more resources for doing fundamental research when they also adopt strategies that align well with the Flood Control 2015 program. Thus, the work of the "engineer-entrepreneur" can be analyzed using a "front stage" and "back stage" analogy (Hilgartner 2000; Bijker et al. 2009)—: as much as geotechnical engineers stress the need for fundamental research, their ability to actually do that research depends in part on their ability to position themselves in the framework of innovative flood risk management.

The uncertainties pertaining to quantitative methods and data-intensive methods relate to the questions as to whether such methods suffice, and how quantitative research should be carried out. The process of codification effectively black-boxes geotechnical knowledge in the form of a calculation rule or computer code. This can make it more difficult for users to assess the impact of such calculation rules or computer code. Similarly, the discussion on Flood Control 2015 revealed the use of standardized data, neglecting different local conditions. In addition, the design of applications for decision makers, policy makers, and stakeholders indicated further challenges. Knowledge generated by means of elaborate geotechnical models needs to be made accessible to an audience of non-specialists and fitted to the requirements of flood risk management in action. Standardized data may not be compatible with local contexts and conceal problems. A different source of uncertainties became apparent during the discussion on organizational aspects of decision making in a time of crisis, which looked at the influence of the political interests of decision makers and at idiosyncratic local populations who often act according to their own ideas about risks, making their actions less amenable to control.[2]

Conclusion: uncertainty as a source of innovation?

Geotechnical engineers at Deltares are committed to an elaborate process of research to reduce the uncertainties of geotechnical models, and develop state of the art calculation rules that can be used in safety assessments. The value of geotechnical models is based on their success in specific contexts, which emphasizes relevance rather than truth. In practice, relevance may be confused with truth, particularly outside of the laboratory, where dike safety assessments need to be perceived as epistemically up to par in ways that tie in with organizational, institutional, and political requirements. The use of data-intensive methods indicates a commitment to "innovative" quantitative approaches, and the development of software that fosters preparedness. Geotechnical engineering needs to perform not only according to criteria of epistemic robustness (e.g. by producing more accurate calculation rules), but increasingly also needs to meet demands related to "social robustness" (Nowotny 2003). For geotechnical engineers, this can imply the need to become "engineer-entrepreneurs" (Daston and Galison 2007: 398). Engineers need to produce knowledge that is considered to be relevant by their peer community of geotechnical engineers, but also encounter political commitments to flood mitigation in their work. In this sense, geotechnical engineers "back stage" stress the exploratory

capacities of geotechnical models and their limitations. However, "front stage" presentations of such models emphasize representation.

The use of geotechnical models implies a range of uncertainties. Engineers may speak of empirical forms of uncertainty due to the lack of empirical data about soil composition, the complexity of soil behavior, and ensuring the representativeness of physical experiments in the laboratory. The use of geotechnical models outside the laboratory introduces further indeterminacy in the form of organizational challenges in contexts of use. Attempts to develop definitive calculation rules and implement "innovative" technologies for flood risk management can be undermined by uncertainty, defined along the lines of Gross' work as "a situation in which, given current knowledge, there are multiple possible future outcomes" (Gross 2010: 3). Uncertainty can put our highly technological cultures at risk, since the methods chosen to cope with various risks may be out of step with the "multiple possible future outcomes" (ibid.) concomitant with uncertainties. From the perspective of geotechnical engineers, claims to knowledge need to be approached with apprehension—the reliability of geotechnical models does not imply an objective truth, and calculation rules acquire credibility through successful application, which does not mean geotechnical models are complete. However, the black-boxing of knowledge about geotechnical phenomena (e.g. in the form of calculation rules or software) may enable the use of geotechnical knowledge in domains outside of geotechnical engineering where geotechnical models are valued differently.

As became clear, geotechnical modeling may not only contribute to the reduction of uncertainties, but can also lead to awareness of previously veiled uncertainties. Thus, geotechnical modeling may have a disruptive effect in the realm of policy making, since it can lead to new insights about dike failure mechanisms. However, social groups differ in how they value uncertainties (Mackenzie 1999). The settling of knowledge in the form of calculation rules, software, or policies that are considered to be epistemically and/or socially robust is exactly what may put technological cultures at risk. Black-boxed knowledge can imply a diminished ability to evaluate the pros and cons of various approaches to uncertainties, and can preclude the adoption of uncertainties as a source of knowledge about risks. Adopting uncertainty as a source of knowledge involves organizational, institutional, and socio-economic challenges. As much as the tractability of geotechnical phenomena can be questioned and the uncertainties involved with geotechnical modeling can be emphasized, it may not be in the interest of social groups to do so. In addition, phenomena of which societies are ignorant cannot always be quantified and turned into probabilities, since they fall outside of the scope of quantitative practices in technological cultures.

Rather than taking a "wait and see" or "wait-until-more-science-is-available" approach to uncertainties,[3] Gross argues that "surprises" need to be deliberately fostered and appreciated as moments where the precarity of objective knowledge becomes apparent. As a result, social groups can become aware of ignorance, identified as "knowledge about the limits of knowing in a certain area," which "increases with every state of new knowledge" (Gross 2010: 68). Surprises can reveal limits of knowledge, and thereby make social groups aware of phenomena that fall outside of existing modes of knowledge production. The acquisition of knowledge can also reveal ignorance. Social experimentation does not aim to "overcome or control unknowns but to live and blossom with them" (Gross 2010: 34). A failure to recognize the value of uncertainty and ignorance as sources of knowledge can put technological cultures at risk. However, uncertainty as a source of knowledge may be kept at bay as a tantalizing promise that turns out to be difficult to realize in practice—uncertainty and ignorance may simply be usurped by vested interests. Even though social experiments need to face vested interests, uncertainty can act as a promising source of innovative knowledge that enhances the resilience of vulnerable societies.

Notes

1 The water boards are regional authorities in charge of the maintenance of flood defenses, waterways, water quality, and sewage treatment. There are currently twenty-five water boards in the Netherlands. The history of the water boards goes back to the thirteenth century, when they developed an elaborate scheme of taxes and governance structures. The water boards are credited as being the oldest form of democratic governance in the Netherlands.

2 Wynne (1992: 117) mentions "indeterminacy" that results from "real open-endedness in the sense that outcomes depend on how intermediate actors will behave." The various applications related to the Flood Control 2015 program feature indeterminacy in the sense that their functioning and value in evacuation procedures will, at least in part, depend on organizational and human components.

3 Joshua Howe calls this approach the "science first paradigm" (Howe 2014).

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