River Flow 2024 – Carnacina et al. (Eds)
© 2025 The Author(s), ISBN 978-1-032-75721-6

Climate robust ductile dikes

F. den Heijer
HAN University of Applied sciences, Arnhem, The Netherlands

M.A. Van
Deltares, Delft, The Netherlands

ABSTRACT: The Netherlands is facing a large dike reinforcement task. Approximately 2,000 kilometers of a total of about 3,500 kilometers must be reinforced before 2050, most of them in the rivers area. Climate change is expected to pose an even larger challenge in the future. The current Dutch approach, in which dikes are made increasingly higher and wider to limit the risks is expected to cause spatial problems. We must therefore develop practical alternatives. The concept of strong-flexible or ductile dikes, which breach only slowly in case of overloading, reduce the risk of flooding and use less space due to construction and the dike material used. At present no practical method to define, quantify and economically evaluate the ductility of dikes is available. This paper presents the set-up of a project elaborating the concept. It will answer the question to what extent and in what way the long-term climate robustness of dikes can be increased by means of ductile dikes. The research is pending and is carried out by a consortium of knowledge institutions, government, water boards, consultancy firms and contractors.

1 INTRODUCTION

In the Netherlands dikes have been built from the early Middle Ages. About 60% of the Netherlands is flood prone. In former days, the height and construction of dikes were mainly based on experience. After the disaster in 1953, during which 1836 people died, a more scientific and quantitative approach was developed. Safety standards were established based on simplified risk assessments (van Dantzig, 1956). Based on these standards design rules are developed, dikes are strengthened, and storm surge barriers have been built (van de Ven, 2004). To secure safety against flooding, safety standards are established by law since 1996. These standards are updated based on a more sophisticated risk assessments in 2017 (Ministerie van Infrastructuur en Milieu, 2016). A periodic assessment is required by law as well. In the Netherlands, for the majority of the dike length waterboards are responsible for the dike management, and that includes this periodic safety assessment. In case a dike does not meet the standards it enters the National Flood Protection Program, in which the dike reinforcements are planned and financed since 2008.

The Netherlands is facing the largest dike reinforcement task since the program called Delta Works, which was executed after the 1953 disaster. About 2,000 kilometers of a total of approximately 3,500 kilometers must be reinforced before 2050, most of them in the rivers area. Climate change is expected to pose an even larger challenge in the future. The economy and number of inhabitants behind the dike is increasing due to, among others, growing city centers and expanding industries. The current Dutch approach, in which dikes are made increasingly higher and wider to limit the risks causes spatial problems in the long term in

DOI: 10.1201/9781003475378-131

most of the densely occupied country. We must therefore develop practical alternatives that balance spatial planning and safety against flooding.

Strong-flexible or ductile dikes reduce the risk of flooding. In (den Heijer & Kok, 2022) the ductile dike behavior is defined as 'a slow failure process of a dike, and a relatively slow or depth-limited breach growth, both leading to reduced breach dimensions and reducing flood impacts'. In terms of personified features, you could describe it as a dogged ductile dike. Since in this concept the time during dike-breaching is important for the risks of flooding, they expect that 'integrated risk assessment, based on a time-dependent physical model, provides the insight in the difference in risks between brittle and ductile dikes'. Together with the difference in costs this enables the trade-off of dike designs. This trade off may result in the use of different dike material leading to reduction of needed dike dimensions, or in a more resistance and resilience behavior with respect to climate change. The opportunities for ductile dikes in the framework of a changing climate are being researched in a Dutch project 'Climate robust ductile dikes' executed by participants from government, water boards, knowledge institutes, consultancy firms and contractors.

In this paper we present the set-up of this project. We start with an overview of flood risk management developments (section 2) and relevant recent studies (section 3). Next, we present the set-up of the project 'Climate robust ductile dikes' (section 4). Finally, we present the pending discussions about definitions and considerations for design and management (section 5).

2 DUTCH FLOOD DEFENCE MANAGEMENT RELATED TO RIVER MANAGEMENT

Main rivers in the Netherlands are the Rhine and the Meuse. In the early middle ages the people lived on high grounds between and along the rivers, and were fishers (van de Ven, 2004). Obviously, the risk management consists of reduction of consequences of floods by living on high grounds that were rarely reached by the floods.

The monks started to build the first protection against flooding with small quays of clay to protect larger areas of land and developed agricultural potential in the fertile flood plains. In course of time these quays were connected to closed rings of small dikes, reducing the room in the flood plains. The enclosed land, however, was prone to floods, devastating the crop and properties. Obviously, the risk management was adapted to reduce the probability of floods. At that time flood defence management was organised by the local community.

In the Middle Ages, the quay-heights were increased to small dikes for better protection of the enclosed areas. Irrigation of the enclosed areas caused subsidence by which potential flood depths increased. Consequently, the consequences of floods led to more damage and casualties. Therefore, the flood defences were further increased in height. The risk management focused more and more to reduce the probability of flooding by reinforcing the dikes. Flood defence management was then organised more and more for in small regions by water authorities. The flood risk management was mainly based on experiences of previous floodings and water levels.

In the late Middle Ages, the farmers build dikes in the remaining floodplains in order to increase their agricultural potential. This further decreased the room for the river. In the 18th century the number of floods increased drastically. Due to inter-regional cooperation some large measures were taken, such as digging the Pannerdensch Canal (1701-1709) to better divide the water discharge between the river branches (Van Heezik, 2007). A National Public Works authority was established in 1798 (Rijkswaterstaat). From that time a number of measures were taken to streamline and train the river to better navigate as well as discharge the river water. The risk management is still focused on reducing the probability of flooding, however, also by decreasing the loads. As a result, in the course of the 19th century the number of flood disasters decreased.

In the 19th and 20th century, the Rhine became more and more an important transport corridor from the major harbor of Rotterdam to the hinterland. The Meuse has been used for cole transport since early 20th century. This use changed during the last decades to the transport of building materials i.e. sand and gravel. In the 20th century, the 1953 flood disaster introduced a large incentive for a more scientific approach for flood risk management (Deltacommissie, 1960). Law-backed standards for flood defences lead to a further focus on limiting the probability of flooding by assessing, monitoring and adapting dike strengths. National financing caused a shift from (inter-)regional cooperation to national supervision of water authorities for flood defence management.

The high-water levels and near-disasters of 1993 and 1995 in the Rhine led to a renewed discussion on the standards against flooding. The program Room for the River focused on measures for reduction of the probability of floods by decreasing the loads. Instead of supervising water authorities, cooperation between national regional and local level was required because the extra room for the river caused relocation of dikes and thus a change in flood risk management and spatial planning.

The concept of 'Delta dikes' was developed, brought up by the 2nd Delta commission, which consists of dikes which are so wide, high or strong that they would not breach (Delta Commision, 2008). However, are these concepts feasible, affordable and possible to build? Climate change, effecting flood risk, made it necessary to also prepare for unforeseen dike failures. Therefore, the last decades, the risk management also focusses more on reduction of the consequences of flooding by early warning, preparedness and evacuation planning. The Meuse summer flood in 2021 forced to face unforeseen high-water levels, resulting in the conclusion that absolute safety is not possible. Preparedness is also necessary.

In retrospective, the main focus on components of risk, being loads and strengths (hazards) and consequences of flooding (sometimes divided in exposure and vulnerability) (Thywissen, 2006) alternated over the centuries, but none of the three became unimportant. The topic of this paper further focuses on reducing the consequences of flooding by an alternative construction of dikes. This alternative construction is focused on having additional time during floods for repair, reduction of flood volume, or evacuation.

3 RESEARCH ON DIKE STRENGTH, FAILURE PATHS AND DUCTILITY

The international research related to dike safety focused in the last century consecutively on different parts of the risk-chain. In the decades after the disaster of 1953 and with the emerging of computer capacity, numerical modeling of loads in rivers and seas emerged. First focus was the dike height, with as main aspect the wave run up and overtopping (J. W. van der Meer, 2002). Other failure mechanisms followed. A lot of the research carried out on dike strengths in the last decades is summarized in the International Levee Handbook (CIRIA, 2013). Research on probabilistic methods for flood defence systems intensified in the last 25 year of the 20th century (Kortenhaus, 2003) (Steenbergen et al., 2004). Since probabilistic methods require the evaluation of an exploding number of different load and strength situations, the use of look-up tables (for loads) and fragility curves (for strength) increased (Vorogushyn et al., 2009). Since the 90ties a lot of effort has been put in the modelling of floodings and the consequences (De Bruijn & van der Doef, 2011). Last decades Risk management is upcoming (Poljansek et al., 2019) to optimally align the governance of different parts in the risk reduction process.

The first steps towards the incorporation of residual strength became popular in the last years. For a long time, researchers and politicians realize the strength of a dike is (much) more than the resistance against an initial failure mechanism. Even in the first Delta Commission assumed the frequency of the probability of flooding was at least a factor 10 times lower than the high tide for which the dike was designed (Deltacommissie, 1960). Only after the establishment of the new safety standards in 2017, which were based on the probability of flooding and which numbers were much more stringent than the ones before which were based on load frequencies, the development of failure paths emerged (Rosenbrand & Knoeff, 2020) (van den Ham, 2020). In (A. W. Van Der Meer et al., 2022) the concept is applied for the dike reinforcement project SAFE along the Lek river, focus on slope instability as initial failure mechanism.

Even a step further is the concept of ductility, realizing a dike which is eroding during a failure path (Van et al., 2022), the dikes' shape changes during this process. This concept is about reducing potential impacts. Brittle dikes will break rather suddenly, with a fast breach growth process leading quickly to a large breach width. A ductile dike will break slowly, giving time for the inhabitants to evacuate, and for the dike managers to take emergency measures. After failure the dikes breach will grow only slowly, leading to a small breach width and far less impact of flooding than a brittle dike failure. The concept and modelling for the failure mechanisms piping and overtopping is presented in (den Heijer & Kok, 2022). Appearances of ductile dikes are:

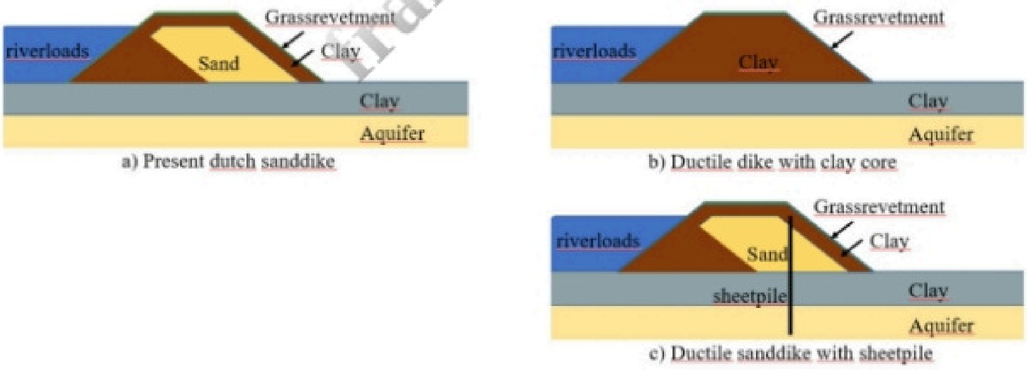
- Dikes of erosion resistant clay or equivalent resistant material. This may be placed in the core, on the riverside as suggested in (Van Den Hoven et al., 2023), or at the land side in a stability berm, all meant to reduce inflow in case of dike breach.
- Dikes with sheet piles which are stable in case of overtopping and damage. Sheet piles are used to prevent piping or for dike stability. In case they are designed to be stable as well in case of dike damage through i.e. erosion through overtopping and even overflow, they prevent the enormous inflow, which would occur in case of complete collapse.
- Very wide dikes, an appearance of delta dikes as well in (Delta Commision, 2008), which prevents high flood impacts due to the time the failure path takes before breaching, and consequently the smaller breach widths.

4 PRESENT RESEARCH ON DUCTILE DIKES

The research, granted as SU1789 by the Taskforce for Applies Research SIA, part of The Dutch Research Council NWO, answers the following main question: *To what extent and in what way can the long-term climate robustness of dikes be increased by means of strong-flexible or ductile dikes?*

We are investigating the practical options for ductile dikes, behaving with a slow failure process, and developing a relatively slow or depth-limited breach growth, both leading to reduced breach dimensions and reduced flooding impacts. Next to the time available during flooding, an important advantage of ductile dikes is that the spatial use may be limited by an alternative dike structure and material use.

Figure 1 shows 3 different appearances of dikes as presented in (den Heijer & Kok, 2022), from which b) and c) are supposed to be more ductile than a) due to respectively the clay core, which erodes much slower than the sand core, and the sheet pile, which reduces the flood volume significantly, because it will either withstand or substantially reduce breach grow during overflow.



a) Present dutch sanddike

b) Ductile dike with clay core

c) Ductile sanddike with sheetpile

Figure 1. Appearances of dikes with different degrees of ductility.

There is not yet a practical method to define, quantify and economically evaluate the ductility of dikes. It is also not clear how climate robust they are over their lifespan. The aim of the research is therefore to generate practical insight into the climate robustness of ductile dikes, in order to give guidance to policymakers, consultants and contractors and show concrete cases of this new dike reinforcement option. The research questions are:

1. How can the ductility and climate robustness of dikes be expressed, so that different designs can be compared?
2. What toughness do our current dikes have, and what management efforts, reinforcement costs and risks do we (apparently) accept given the legally established standards?
3. How can ductility be achieved in the design of dikes?
4. How climate robust are our current dikes and current designs?
5. To what extent does the climate robustness of ductile dikes differ from that of current dikes?
6. How can we increase the ductility of the existing dikes in order to have a more climate-robust flood risks reduction system in the long term?

The research questions are studied in 3 work packages. First, we consider the ductility in our current dike design (work package 1). Subsequently, examples for ductile dikes are developed and small-scale tests are performed (work package 2). Existing and new dike design are assessed for climate robustness by a stress test (work package 3). The synthesis of these work packages results answers the main research question. The research is performed with twelve partners from government, water boards, knowledge institutions, consultancy firms and the construction industry.

5 CONCLUDING DISCUSSION

An inventory of examples of ductile dikes has been performed and an inventory of definitions and decision-making aspects of ductile dikes and climate robustness has been described.

The inventory led to a number of cross sections which provide examples of existing dikes with assumed ductile behavior, providing an overview of most important features of ductile dikes:

- Limited inflow due to the slow breakthrough process. It is obvious that delay of breakthrough after occurrence of an initial failure mechanism, lead to delay of the inflow. In Figure 2 this would mean the start of the inflow leading to the increase of polder water levels (blue) would shift to a later time. This would lead to a limited total inflow volume of water into the hinterland.
- Limited inflow due to the slow breach growth process with limited breach width and depth. The difference between breach growth of sand or clay dikes is significant (Verheij, 2003), consequently effecting the inflow.
- Warning time due to the clear and monitorable process during a failure path, providing opportunities for repair and evacuation. In case the dike erodes or appears to be instable by starting to slide as a part of a failure path, a ductile dike provides time to take emergency measures.

The materials and construction method of a dike are seen as most important to get these ductility features. Building ductile dikes may require more budget, but this is certainly not always the case. Maybe less volume of materials is needed, or less room for the dike is needed. And some of the effects of building in ductility reduces flood risks: the expected damages are lower due to the reduced inflow of water volume. However, the most important motive to be protected by a ductile dike compared to a brittle dike, is the reduced risk of casualties due to drowning.

A practical definition of a ductile dike is ‘a dike which its construction is meant to delay the breakthrough process in case of overloading, and to limit breach widths reducing the inflow of water into the hinterland’. To take maximum advantage of ductility, it should be incorporated into the design in such a way that the failure mechanisms that could quickly lead to large breaches develop substantially slower than others. In the project we use a definition of climate robustness as the extent to which the consequences of malfunctioning of a structure during its lifespan are insensitive to unforeseen climate change.

The lifespan of dikes is in general many times longer than that of a concrete structure. Many dikes in the Netherlands exist already several centuries or longer. Therefore, an important consideration to construct ductile dikes is the management during its lifetime. A feature of a ductile dike is that after initial failure the dike may be damaged without breaching. Following this feature the dike could be damaged several times during its lifespan. Most dikes are designed for a horizon of 50 years. An event which causes dike damage will require immediate repair which costs could be in the order of magnitude of a regular reinforcement. In case the event occurs rather quickly after a reinforcement it would require additional budget. Since the safety standards are stringent the effect on life cycle costs is assumed to be limited.

Concluding, this paper presents the motive and fist steps in the research on ductile dikes, meant to gain insights for practical applicability and affordability. This is a necessary step in its promotion from a promising and challenging alternative to reduce risks (especially on casualties) and to save space, into an option for the reinforcement task of the Dutch National Flood Protection Program.

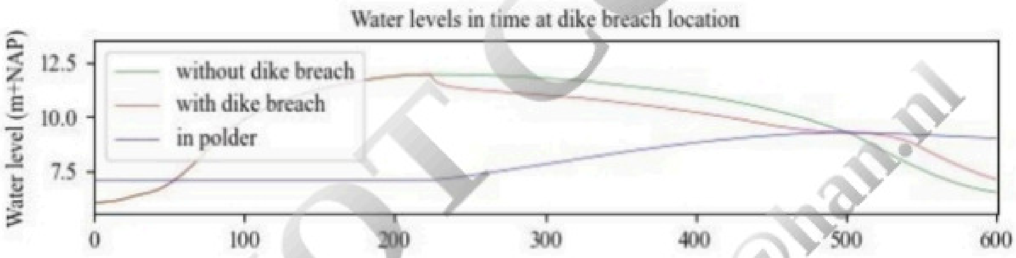


Figure 2. River flood wave near Wageningen (green), effected by a breach (red), and the polder water levels (blue), adapted from (den Heijer and Kok, 2022). Time in hours on the x-axis. NAP is the Dutch reference level.

REFERENCES

CIRIA. (2013). *International Levee Handbook*. CIRIA, Griffin Court, 15 Long Lane, London, EC1A 9PN, UK.

De Bruijn, K., & van der Doef, M. (2011). *Gevolgen van overstromingen - Informatie ten behoeve van het project Waterveiligheid in de 21e eeuw*.

Delta Commision. (2008). *Samen werken met water - Een land dat leeft, bouwt aan zijn toekomst Bevindingen van de Deltacommissie 2008*.

Deltacommissie. (1960). *Rapport Deltacommissie - Eindverslag en interimadviezen*. Staatsdrukkerij- en uitgeversbedrijf.

den Heijer, F., & Kok, M. (2022). Assessment of ductile dike behavior as a novel flood risk reduction measure. *Risk Analysis*, 1–16. https://doi.org/10.1111/risa.14071

Kortenhaus, A. (2003). *Probabilistische Methoden für Nordseedeiche*. Technischen Universität Braunschweig.

Ministerie van Infrastructuur en Milieu. (2016). *Wet van 2 november 2016 tot wijziging van de Waterwet en enkele andere wetten (Waterwet)*. https://wetten.overheid.nl/BWBR0025458/2021-07-01

Poljansek, K., Casajus Valles, A., Marin Ferrer, M., De Jager, A., Dottori, F., Galbusera, L., Garcia Puerta, B., Giannopoulos, G., Girgin, S., Hernandez Ceballos, M., Iurlaro, G., Karlos, V., Krausmann, E., Larcher, M., Lequarre, A., Theocharidou, M., Montero Prieto, M., Naumann, G., Necci, A., … Wood, M. (2019). *Recommendations for National Risk Assessment for Disaster Risk Management in EU*. https://doi.org/10.2760/147842

Rosenbrand, E., & Knoeff, J. G. G. (2020). *KvK 2019 onderzoek faalpaden en piping*. https://doi.org/11203719-028-GEO-0009

Steenbergen, H. M. G. M., Lassing, B. L., Vrouwenvelder, A. C. W. M., & Waarts, P. . . (2004). Reliability analysis of flood defence systems. *Heron*, *49*(1), 51–73.

Thywissen, K. (2006). *Components of Risk - A Comparative Glossary*.

van Dantzig, D. (1956). Economic Decision Problems for Flood Prevention. *Econometrica*, *24*(3), 276. https://doi.org/10.2307/1911632

van de Ven, G. P. (2004). *Man-made lowlands. History of water management and land reclamation in the Netherlands*. Matrijs.

van den Ham, G. (2020). *Faalpadenanalyse macrostabiliteit binnenwaarts*. https://doi.org/11203719-027-GEO-0001

Van Den Hoven, K., Van Belzen, J., Kleinhans, M. G., Schot, D. M. J., Merry, J., Van Loon-Steensma, J. M., & Bouma, T. J. (2023). *How natural foreshores offer flood protection during dike breaches: An explorative flume study*. https://doi.org/10.1016/j.ecss.2023.108560

Van Der Meer, A. W., Kanning, W., Schweckendiek, T., Van Veen, N. J., Den Heijer, F., & Jongejan, R. (2022). *INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING A design approach for levees considering the failure path of inner slope instability Une méthode de design des digues considérant les événements qui suivent l'instabilité initiale du talus interne*. https://www.issmge.org/publications/online-library

van der Meer, J. W. (2002). *Technisch Rapport Golfoploop en Golfoverslag bij Dijken*.

Van Heezik, A. A. S. (2007). *Strijd om de Rivieren*. Technical University of Delft.

Van, M. A., Rosenbrand, E., Tourment, R., Smith, P., & Zwanenburg, C. (2022). *Failure paths for levees*. https://doi.org/10.53243/R0006

Verheij, H. (2003). *Aanpassen van het bresgroeimodel in HIS-OM*.

Vorogushyn, S., Merz, B., & Apel, H. (2009). Development of dike fragility curves for piping and micro-instability breach mechanisms. *Natural Hazards and Earth System Science*, *9*(4), 1383–1401. https://doi.org/10.5194/NHESS-9-1383-2009