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REVIEW ARTICLE

A comprehensive review on structural tsunami countermeasures

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Abstract
Tsunamis pose a substantial threat to coastal communities around the globe. To counter their effects, several hard and soft mitigation measures are applied, the choice of which essentially depends on regional expectations, historical experiences and economic capabilities. These countermeasures encompass hard measures to physically prevent tsunami impacts such as different types of seawalls or offshore breakwaters, as well as soft measures such as long-term tsunami hazard assessment, tsunami education, evacuation plans, early-warning systems or coastal afforestation. While hard countermeasures generally aim at reducing the inundation level and distance, soft countermeasures focus mainly on enhanced resilience and decreased vulnerability or nature-based wave impact mitigation. In this paper, the efficacy of hard countermeasures is evaluated through a comprehensive literature review. The recent large-scale tsunami events facilitate the assessment of performance characteristics of countermeasures and related damaging processes by in-situ observations. An overview and comparison of such damages and dependencies are given and new approaches for mitigating tsunami impacts are presented.

Keywords Tsunami countermeasure · Hard countermeasure · Structural countermeasure · Tsunami mitigation · Extreme-wave events

1 Introduction

Many coastal communities are exposed to the hazards of marine flooding induced by tsunamis or storm surges resulting in adverse impacts on the coastal ecosystem and built environment. The highly destructive energy of tsunamis can cause large numbers

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Fig. 1 Broad classification of structural tsunami countermeasures

of casualties, damages to infrastructure and affect the livelihood of coastal communities. The threat due to tsunamis intensify since the already densely populated coastal areas are experiencing further population growth as predicted by Neumann et al. (2015). From 625 million people in 2015, the population growth in low-lying coastal areas is expected to raise by 68–122% resulting in about 1052 to 1388 million people by 2060 (Neumann et al. 2015). The Indian Ocean Tsunami (IOT) on the Boxing Day of 2004 was the most destructive recent tsunami with about 230,000 fatalities (Telford et al. 2006). Apart from instantaneous destruction, tsunamis can cause medium-term impacts such as the destruction of power plants and long-term impacts such as salt-water intrusion in intensely cultivated delta plains (Villholth and Neupane 2011; Nakamura et al. 2017), which may be mitigated by hard or soft tsunami countermeasures. Although, in several potentially affected locations, authorities operate state-of-the-art tsunami early-warning systems, the available time for alerts or the evacuation of the threatened coastal population is often insufficient and the possibility of malfunctions cannot be ruled out (UNDRR 2019). For instance, the 2004 IOT reached the town of Banda Aceh in northern Sumatra within 15 min after the earthquake. The danger of a malfunctioning of early warning systems can aggravate the effects of insufficient additional countermeasures (Strunz et al. 2011; Bernard and Titov 2015; Samarasekara et al. 2017). For instance, in the area around Hikkaduwa City in Sri Lanka, about 47% of the residents do not trust in the functionality of the present early-warning tower since it failed during the 2012 Sumatra tsunami (Samarasekara et al. 2017). Furthermore, the damages to crucial infrastructure, e.g. communication, freshwater supply, industry or agriculture, are unavoidable, even through early warnings, if the structures are not designed to resist the impact of a tsunami (Palermo et al. 2013). Esteban et al. (2013) claim that combinations of hard and soft countermeasures (multi-layer approaches) should be promoted in tsunami-prone areas. The present review provides an overview on hard tsunami countermeasures classified as having blocking, steering or slowing character. The main body of the review is divided into three sections as projected in Fig. 1. In order to limit the extent of the present review, soft countermeasures (e.g. vegetation belts, risk management) are not considered in detail here.

2 A brief overview on structural tsunami countermeasures

For protecting coastal settlements from tsunami impact, different mitigation measures are adopted depending on the regional tsunami impact assessment, tsunami awareness and economic capability. Even if existing hard tsunami mitigation measures are often effective against frequently occurring high-energy wave events (Sato 2015), recent tsunami events have shown that such countermeasures and their design need to be improved to withstand the impact of extreme tsunami events of unexpected magnitude in some areas. Focusing on tsunamis, such events may be divided into Level 1 and Level 2 tsunamis, where Level 1 events describe tsunamis with a return period of 50–160 years with inundation depths below 10 m while Level 2 tsunamis have a return period of hundreds to thousands of years with inundation depths above 10 m (Shibayama et al. 2013). As an example for a Level 2 tsunami, the 2011 Tohoku Tsunami has shown that several of the Japanese defence structures were not designed to withstand the tsunami force that unfolded during the event and that exceeded most recent historical events (Suppasri et al. 2013; Takagi and Bricker 2015; Goltz and Yamori 2020). However, as a highly exposed country, Japan has a long history in tsunami research (Shuto 2019). To the best knowledge of the authors, Matuo (1934) and Takahasi (1934) were the first to conduct laboratory experiments for examining the effectiveness of seawalls as tsunami mitigation measure. Prior to the Chile Tsunami in 1960, Japan enforced its tsunami countermeasures broadly and during the Chile Tsunami (and the Ise Bay Typhoon in the year before), the installed countermeasures proved their effectiveness. Based on this positive experience the "Chile Tsunami Special Measures Law" was revealed and floodgates and breakwaters were planned as additional countermeasures for preventing tsunami penetration into rivers and bay mouths (Shuto 2019). After the 2011 Tohoku Tsunami, structural and non-structural countermeasures have been reinforced again (Strusińska-Correia 2017).

In 1933, three months after Japan was exposed to a large tsunami, the Council on Earthquake Disaster Prevention (CEDP) of Japan released ten tsunami countermeasure rules (CEDP 1933; Shuto and Fujima 2009). In addition to the suggestions of CEDP (1933), the manuals of the National Oceanic and Atmospheric Administration of the USA (NOAA 2001) and UNESCO (2011) also proposed concepts for mitigation measures. In general, tsunami mitigation measures can be broadly divided into constructional, hard countermeasures, such as dikes and seawalls, and soft countermeasures encompassing nature-based solutions (e.g. coastal afforestation) and those based on the management of the tsunami impact (e.g. evacuation plans, creating public awareness), as projected in Table 1. CEDP (1933), NOAA (2001) and UNESCO (2011) sometimes use divergent terms that describe basically the same concept or depict a subgroup of each other (e.g. relocation of dwelling houses is a subset of general rezoning). Such diverging terminology is addressed in Table 1. In this paper, only constructional hard countermeasures are considered which have been also discussed by Yamamoto et al. (2006), Kreibich et al. (2009) and Strusińska-Correia (2017), for example.

Common constructional mitigation measures (Fig. 2) are designed to avoid or attenuate tsunami impact on the coast and structures, by preventing direct wave impact or dissipating the tsunami impact energy. Today such measures are intended to prevent or mitigate the impact of Level 1 tsunamis. For Level 2 tsunamis, constructional countermeasures may be able to mitigate the tsunami impact to a certain extent or provide additional evacuation time. However, they may not have any mitigating effect at all for Level 2 tsunamis (PARI 2011; Shibayama et al. 2013; Goltz and Yamori 2020). Following UNESCO (2011)

Table 1 Tsunami mitigation techniques grouped following constructional and management approaches

Concept	CEDP (1933)	NOAA (2001)/UNESCO (2011)
Constructional	Relocation of dwelling houses to high ground	Retreating/avoiding/accommodation
Constructional	Coastal dikes	Blocking/protection
Constructional/tsunami-based impact mitigation	Tsunami control forests	Slowing (blocking)
Constructional	Seawalls/dykes	Blocking/protection
Constructional	Tsunami resistant areas	Retreating
Constructional	Buffer zone	(Retreating)
Management	Evacuation routes	Management
Management	Tsunami watch	Early warning
Management	Tsunami evacuation	Management
Management	Memorial events (awareness)	Management

and NOAA (2001), basically three structural options for preventing/mitigating the risks of damage or loss are available:

1. Structural (protecting; Fig. 2a, b, c, e).
2. Retreating (accommodating, Fig. 2d).
3. Non-structural measures.

The countermeasures presented in Fig. 2 cannot be applied at every potentially threatened coast and, depending on the regional setting, the optimum option needs to be applied by the responsible authorities. The mitigation measures provided by the NOAA and UNESCO can significantly reduce the expectable damage exerted by an extreme coastal hazard, but certain crucial shortcomings need to be considered.

Option a) Blocking with several options can easily be implemented in a developed environment. However, the structures need to be designed to resist the loads of extreme events, and construction schemes need to be carefully planned as they are site specific. The structures planned under this option should also allow acceptable risk. Further, uncertainties arise from possible amplifications due to reflection and redirecting of waves to unintended directions, which might happen in densely populated locations or in the vicinity of important infrastructures. The space between the protected structure (e.g. a dwelling unit) and the protection measure (e.g. the blocking wall) could function as a stilling basin, probably inducing wave oscillations between them. This effect, consequently, might lead to hydrodynamic forces on the above stated shore-based structures that are higher than for the case without protection measures. Considering Level 2 tsunamis, blocking has often shown to be an unreliable and insufficient countermeasure (e.g. Onishi 2011; Takagi and Bricker 2013). However, it is subject of research and there is debate as to whether certain measures (i.e. breakwaters) can mitigate flow velocities and heights, at least regionally (e.g. Tomita et al. 2011; Aldrich and Sawada 2012).
Option b: Avoiding is only realisable if considered during the planning phase of construction and developing an area. Following the guidelines of NOAA (2001), this option encompasses constructions above inundation levels (in fact on higher ground and/or

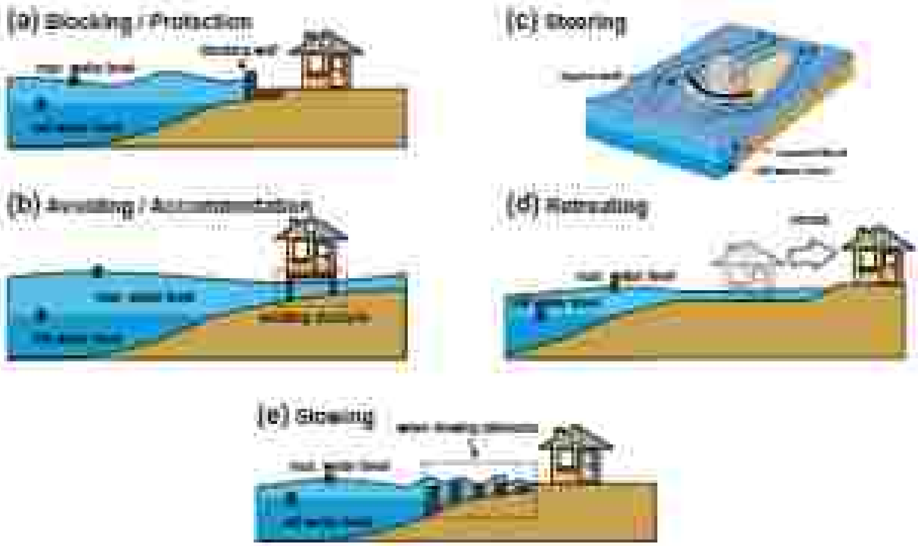

Fig. 2 Basic strategies to reduce tsunami risk following NOAA (2001, modified)

at greater (longer) distance from the shore, which is preferable in undeveloped areas) or building over elevated structures such as piers or hardened podiums. However, even if avoiding might be preferred for undeveloped stretches of the coast, it is not applicable after development and therefore ineligible for subsequent reinforcements of coastal areas (Cruz 2014). Avoiding in the sense of elevated structures can be sufficient for Level 1 tsunamis. For Level 2 tsunamis, the required construction heights will most probably exceed any reasonable cost-benefit ratio and the structural stability would still be questionable.

Option c: Steering requires more space between protected structures and the shoreline. This option may focus the flood along adjoining structures and may also be dangerous to the community due to increased flow velocities. Due to the above stated facts, this option is unsuitable for coastal areas of dense development and is not a suitable option for Level 2 tsunamis.

Option d: Retreating is, in consequence, the ultimate mitigation measure against high-energy wave impact, if the retreat area is chosen with a sufficient distance and/or height to the shoreline. However, retreating is an immense intervention for local population and is only applicable in recently affected areas or areas under initial or planned development. Most countries publish a related setback line for planning of coastal infrastructure that depends on the frequency and magnitude of the coastal hazards (Simpson et al. 2012; Coastal Wiki 2020). Retreating can avoid the impact of Level 2 tsunamis on populated areas if the distance is chosen sufficiently. However, the retreat of whole existing coastal cities or villages is not a realistic option for most of such populated areas.

Option e: Slowing is viable in areas that are already densely developed, requires lesser space and is economically feasible in most cases. Slowing the wave impact by macro-roughness elements that can act as dissipators can be adopted for reducing the wave run-up and inundation distance. However, the information on the nature, physics and effectiveness behind such dissipators is scarce till date, with no proper design guidelines in place. The main target of countermeasures aiming at slowing is Level 1 tsunamis.

However, if designed in sufficient dimensions a mitigating effect may be possible in regard of Level 2 tsunamis.

3 Hard tsunami mitigation measures

3.1 General

The two mainly adopted constructional mitigation techniques (Table 2) are likely the construction of continuous or detached breakwaters (Fig. 3a), either of submerged or emerged types (blocking/slowing) or massive seawalls (Fig. 3b, c; Mikami et al. 2015). Sea dikes (Fig. 3d) are usually applied for protecting low-lying areas against flooding. The understanding of hydrodynamic processes on such structures and their mitigation capability are discussed by several authors in detail (e.g. Oshnack et al. 2009; Al-Faesly et al. 2012; Elchahal et al. 2009; Rahman et al. 2014; Mikami et al. 2015; Chock et al. 2016; Chaudhary et al. 2018; Ning et al. 2017; Sing 2019; Lawrence and Nandasena 2019), with some authors questioning their efficacy (e.g. Nateghi et al. 2016). Both types of countermeasures have their own functionality, advantages and disadvantages.

3.2 Breakwaters

Detached breakwaters (Fig. 3a) have the original purpose to reduce beach erosion. However, the installation of multiple detached breakwaters, each of comparably small dimension, can mitigate wave impact on the shore by wave reflection and energy dissipation. Detached breakwaters are normally designed as low-crested rubble-mound structures. The comparably small height of detached breakwaters allow significant wave overtopping during storm or tsunami events. Beside detached breakwaters, non-detached breakwaters are often applied to mitigate wave impact and create tranquillity (e.g. in harbours). Breakwaters can be divided into two main types: with sloping or vertical-fronts. Another type of breakwaters, floating breakwaters, is only applied in areas of mild wave climates and are not suitable as protection against tsunami impact (Burcharth and Hughes 2003), and are not discussed here. The construction of breakwaters is a significant intervention in the water ecology with potentially negative impacts on the environment (Dugan et al. 2011 and references therein). Further resentments arise from the possible negative consequences on tourism (Nateghi et al. 2016; Reniers 2019).

A comprehensive overview on possible breakwater failures during tsunami impact has been reported by the National Institute for Land and Infrastructure Management, Japan (NILIM 2013a; Raby et al. 2015). A key lesson from the breakwater failures in 2011 was that such failures are connected to scour on the lee side due to wave overtopping. Subsequently, it was recommended to strengthen the lee side of breakwaters by providing proper toe protection and to provide innovative crown shapes for redirecting the flow towards the sea (NILIM 2013b; Raby et al. 2015). Esteban et al. (2009) conducted physical experiments on the stability of breakwaters and found that the breakwater location is a crucial parameter defining its resisting capability. In deep water, the breakwater is reported to be washed away when hit by a tsunami, while it is able to withstand the impact in shallower waters (Esteban et al. 2008a, b, 2009). In contrast, Hanzawa and Matsumoto (2012) described that breakwaters in shallower water are more damaged by solitary wave impact compared to breakwaters in deeper water. However, Esteban et al. (2015a, b) and references

Table 2 Blocking and dissipating constructions (after USACE 2011)

Type	Function	Objective
Sea dike	Prevent or alleviate flooding by the sea of low-lying land areas	Separation of shoreline from hinterland by a high impermeable structure
Seawall	Protect land and structures from flooding and overtopping	Reinforcement of some part of the beach profile
Breakwater	Shelter harbour basins, harbour entrances, and water intakes against waves and currents	Dissipation of wave energy and/or reflection of wave energy back into the sea
Detached breakwater	Prevent beach erosion	Reduction of wave heights in the lee of the structure and reduction of longshore transport of sediment
Reef breakwater	Prevent beach erosion	Reduction of wave heights at the shore
Floating breakwater	Shelter harbour basins and mooring areas against short period waves	Reduction of wave heights by reflection and attenuation

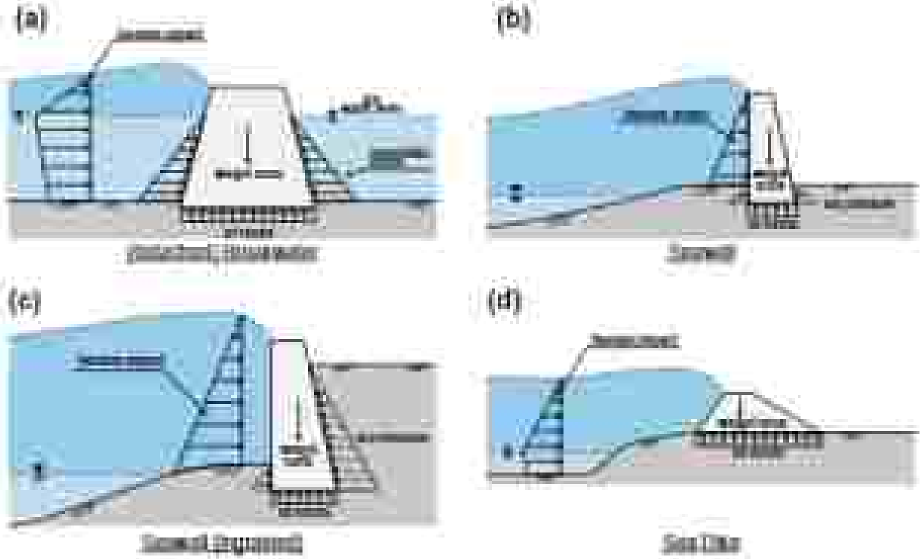

Fig. 3 Schematic setups and applications of breakwater (a), seawalls (b, c), and sea dikes (d), and the connected dominating forces during the impact of the initial tsunami wave

(herein) reported that the most destabilizing process occurs during overflow of the breakwater and that the approach of solitary waves as destabilizing event is not substantial. Hanzawa and Matsumoto (2013) have stated that detached breakwaters can reduce the run-up by 30% to 90%, when exposed to solitary waves, and that damaged breakwaters can still reduce the wave-induced pressure by about 40%. As projected in Fig. 3, detached breakwaters and seawalls are constructed alongshore and are designed to prevent the lee side against overtopping or flooding (Burcharth and Hughes 2003). In general, detached breakwaters serve as a coastal protection and help to redeposit lost beach substrate. However, the spacing must be carefully planned as it might lead to the generation of rip currents.

3.3 Seawalls, coastal dikes and water gates

Seawalls can either completely protect settlements from tsunami impact or extend the available time for evacuation if they are suitably designed (Samarasekara et al. 2017). However, they also could increase the hazard if they fail or allow overtopping (Reuters 2018). Obviously, seawalls avoid coastal damages if they are designed as non-overtopping structure, otherwise, they are likely to be destroyed by an extreme wave event. Furthermore, even if seawalls have a significant potential to protect coastal areas completely against extreme-wave events, their application is expensive (Reuters 2018). On the other hand, seawalls can create the impression of false security leading to settlement in dangerous areas or reduced willingness or preparedness to evacuate. Nateghi et al. (2016) reported that seawalls of 3 m height in Japan lead to forced development in vulnerable areas and can subsequently result in an increased damage during extreme events.

Several designs exist for sea dikes which are mostly constructed from fine-grained materials like sand, silt and clay with surfaces of grass, asphalt, stones or concrete with or without berms (Burcharth and Hughes 2003). Most seawalls in Japan, as along the

Minami-Sanriku coast, were designed based on the experience from historical tsunamis occurring during the past century. However, considering the regional tsunami spectrum over only short historical periods as a basis for structural countermeasures may be insufficient, as demonstrated by the 2011 Tohoku Tsunami (Kato et al. 2012; Goto et al. 2014; Strusińska-Correia 2017), an event with a recurrence interval of c. 500–800 years (Sawai et al. 2012; Goto et al. 2014). This example clearly shows that long-term tsunami hazard assessment integrating instrumental, historical and geological data is crucial for designing downstream hard and soft countermeasures (Weiss and Bourgeois 2012; Engel et al. 2020). Damage to coastal dikes and seawalls is connected to several processes depending on the structural design. On armoured dikes, it was observed that during the overflow scour occurred on their lee side resulting in destabilisation of the armour layer. Scour failure on the leeward toe of coastal dikes and seawalls is reported as the major failure type during the 2011 Tohoku Tsunami on tsunami countermeasures in Japan. The failure mechanism is attributed to wave overtopping and the resulting turbulent flow at the toe. With decreasing flow velocity, the acting pressure on the bed stratum decreases and coinciding with a rise in the pore pressure gradient, the effective stress within the soil medium is reduced (Tonkin et al. 2003; Jayaratne et al. 2015). Over time, the armour is detached by the overflow enabling further removal of the dike interior (fine sediment, gravel), leading to a general malfunction of the structure (Kato et al. 2012). This type of failure is reported to be independent from additional seaward dike protections with artificial armour blocks like tetrapods.

Japanese seawalls were not designed considering wave overtopping as potential design criteria. Therefore, the leeward toe of the seawalls was not designed to resist destabilising erosional processes, which subsequently lead to overturning or sliding. However, even a failing seawall can possibly reduce the tsunami impact (Goltz et al. 2018). In summary, Jayaratne et al. (2015) identified six main failure types of seawalls and sea dikes during field surveys in the aftermath of the 2011 Tohoku Tsunami, which are described in Figs. 4 and 5. It is stated that seaward toe scour was not often observed during the 2011 Tohoku Tsunami. However, this failure mechanism may occur during the backwash of a tsunami, destabilising the seaward dike armour (Fig. 5b; Jayaratne et al. 2015) as observed by Sundar et al. (2014) elsewhere. Whilst the tsunami impact on vertical walls/seawalls is broadly investigated (e.g. Asakura et al. 2003; Kato et al. 2012; Mizutani and Imamura 2000), the effect of preceding breakwaters is understudied as pointed out by Hanzawa and Matsumoto (2015).

3.4 Effectiveness of breakwaters and seawalls

3.4.1 Breakwaters

The mitigation measures prior to the 2011 Tohoku Tsunami in Japan were less effective due to the failures which were mainly caused by scour at the foundations and sliding/overturning due to hydrodynamic forces. However, even the failed structural mitigation measures are reported to have reduced the wave height and delayed the flood impact by several minutes and, thus, still saved lives (PARI 2011; Goltz and Yamori 2020).

Regarding effectiveness, breakwaters showed divergent performance during the 2011 Tohoku Tsunami. Mikami et al. (2015) investigated detached breakwaters in front of coastal dikes considering the openings between a pair of breakwaters and were unable to obtain a clear relationship between dike damages and the location of breakwater openings. They described cases in which coastal areas on the lee side of breakwaters were clearly

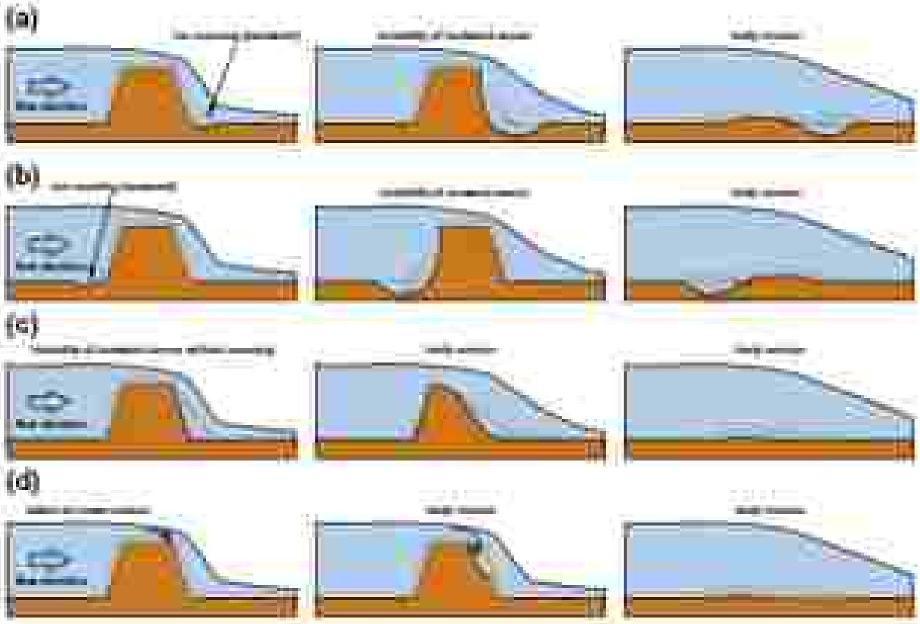

Fig. 4 Dike failure due to overflow-induced erosion. a Scouring on the landward toe, b scouring on the seaward toe, c malfunction of the landward armour and subsequent erosion, d failure of crown armour and subsequent inner erosion (modified and redrawn from Kato et al. 2012 and Jayaratne et al. 2016)

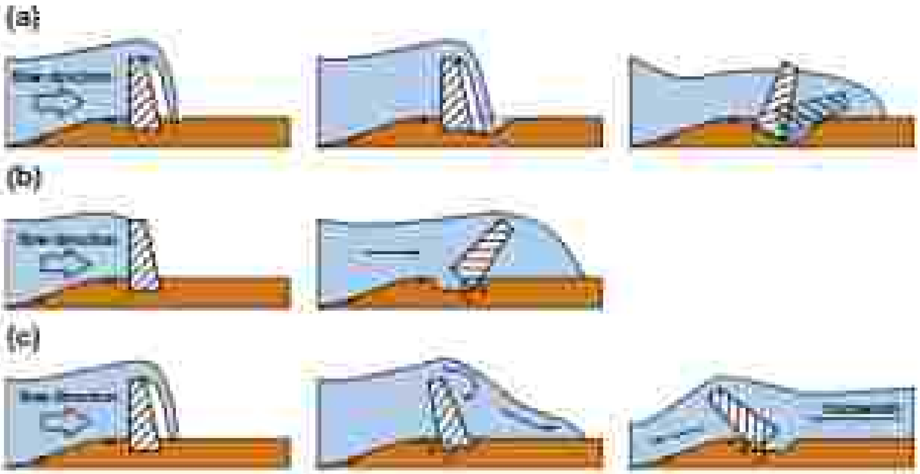

Fig. 5 Typical tsunami-induced seawall failure. a Landward scour leads to seawall instability, b Tsunami impact forces lead to overturning, c The backwash current after overtopping leads to seawall overturning (modified and redrawn from Jayaratne et al. 2016)

protected compared to areas behind the openings. Subsequent experimental investigations indicated an effective breakwater application with a low ratio of the gap between the breakwaters and its distance from the shore (Mikami et al. 2015). However, the world's largest breakwater in Kamaishi (Japan) failed during the Tōhoku Tsunami 2011 resulting in massive damage. Furthermore, the Kamaishi breakwater is suspected to have even increased the tsunami damage due to wave deflection (Onishi 2011). Aldrich and Sawada (2013) concluded that the Kamaishi breakwater was not able to provide any protection to the adjacent town. In contrary, Tomita et al. (2013) have stated that the breakwater was able to reduce the flow velocity and height significantly and provided additional evacuation time (see also Nagheli et al. 2016).

The possibility of increased damage due to insufficiently designed countermeasures of any type (barriers, water gates, tree belts) is also indicated by the tsunami impact at Iwaizumi, Iwate prefecture (Japan) (Ogasawara et al. 2012). Takagi and Bricker (2015) analysed breakwater failures during the 2011 Tōhoku Tsunami numerically and revealed that a breakwater of width below 8 m always suffered damage if the wave height exceeded 14 m. Furthermore, no damage was found at breakwaters broader than 14 m if the tsunami height was below 6 m. In contrary to the overall relations, Takagi and Bricker (2015) were not able to identify significant wave reductions behind the Ishinomaki breakwater (armour block height of 7.00 m above low-water level) and attributed this to the comparably wide openings between the breakwaters. Subsequently, the tsunami was able to enter through these gaps, with an accelerated flow. The case of the Ishinomaki breakwater shows that the use of "permeability" (compare paragraph 5.1) needs to be handled carefully and high attention needs to be paid to the ratio between openings and blocking elements (breakwater elements). However, the numerical investigations were based on 2D simulations with the Delft3D numerical modelling suite. Due to the two-dimensional simulation, vertical velocities and force transfers are neglected. Hence, the simulation suffered from some crucial shortcomings (Bricker et al. 2013; Takagi and Bricker 2015):

- Neglecting vertical motions can result in an enhanced fluid energy.
- The shallow nearshore bathymetry enforces the emergence of bores. This process is not resolved by the horizontal 2D model.

For better understanding of the processes acting during the impact of the 2011 Tōhoku Tsunami, completely three-dimensional numerical models based on sufficiently fine meshes (as recommended in Takagi and Bricker 2015) or even conducted by meshless methods, could be an option if the computational costs can be reduced to permit a practical application.

3.4.2 Seawalls

Based on their post-tsunami surveys, Sundar et al. (2014) and Sundar and Sannasiraj (2018) showed that the seawall constructed over a length of about 300 km along the coast of Kerala at the southwest coast of the Indian peninsula was damaged at several locations mainly due to significant overtopping at lower crest elevations, not only during the 2004 IOT but also during storm wave run-up.

During the 2011 Tohoku Tsunami, the Noda Bay (Noda village, Japan) was protected by two seawall lines (concrete-covered and buttress type) of 10.3 m and 12.0 m height above sea level and a length of 875 m and 300 m, respectively (Ogasawara et al. 2012). Ogasawara et al. (2012) observed that the additional water gates shielding the three rivers crossing Noda village (Myoujin, Ube, Izumisawa) were significantly damaged during the tsunami. The seawalls showed differential effectiveness. While the 12.0 m high seawall did not break at all and only the landward slope was eroded, the 10.3 m high seawall did break. The additionally installed natural barrier of pine trees was also not able to withstand the tsunami. Trunks were broken and trees were washed away causing additional damage to many buildings. In Iwaizumi town the present seawall (design tsunami height 12.3 m) and river water gate were overtopped by the tsunami. Furthermore, both, left and right, riverbanks at the water gate were overtopped resulting in large damages to many houses in the lower areas. In contrary, in Fudai village the installed countermeasures showed a good performance during the same tsunami. Even if the present water gate (15.5 m high) was overflowed during the tsunami, the gate did not fail which is addressed to its design: The Fudai water gate and seawall are connected to the adjacent mountains providing additional stability to the structure (Ogasawara et al. 2012). In Taro town, an X-shaped seawall system of 10 m height existed before the tsunami of 2011, but its effectiveness is questionable (Yamashita 2003; Ogasawara et al. 2012; Tachibana 2013). Based on in-situ observations, Tachibana (2013) was unable to finally determine if the seawalls in Taro town even influenced the inundation pattern. Only for the western edge of the seawalls, the flow direction was influenced notably. It is finally concluded that the seawalls were likely not reducing the damage in Taro, overall.

The uncertainties in the design of structural countermeasures against tsunamis are widely reported in literature and the research community agrees that existing design guidelines (e.g. for breakwaters or seawalls) need to be revised based on the observations of recent tsunami events and that additional advanced mitigation techniques (e.g. combined techniques, systematic plantations) are needed in order to be better prepared for future events (Rahman et al. 2014; Suppasri et al. 2016). In particular, the need for a better understanding of the interaction of tsunamis with countermeasures during the phases of wave impact, flooding and possible backflows has been highlighted (e.g. Palermo and Nistor 2008; Macabuag et al. 2010). Nevertheless, the 2011 Tohoku Tsunami has led to considerable insights into the functionality and effectiveness of breakwaters as tsunami mitigation measure (e.g. Mimura et al. 2011; Takahashi et al. 2014; Mikami et al. 2015; Raby et al. 2015; Strusinska et al. 2015; Suppasri et al. 2016).

3.5 Comparison between seawalls and breakwaters

A summary on the advantages and disadvantages of seawalls and offshore detached breakwaters as coastal protection and tsunami mitigation measures are discussed below.

3.5.1 Seawalls

Seawalls act as mitigation measure against flooding and coastal erosion. Their benefits are: Prevention of hinterland erosion, increased security for property from flooding, physical barrier between land and sea, increased perceived security of local people and maintenance of hinterland value. However, crucial shortcomings are adverse impacts on fronting beaches up to a total loss of them, interruption of longshore sediment movement, disturbance of sediment budgets and coastal ecosystems, increased erosion down drift (terminal scour), and freezing the coast and thus preventing its response to recent and future sea-level rise. The recommended usage of seawalls is to protect high-value hinterland development and to increase and protect amenity usage where other solutions are not suitable. Questions remain, however, regarding overtopping and run-up particularly during tsunamis.

3.5.2 Offshore breakwaters

The benefits of construction of offshore breakwaters as mitigation measures against tsunamis are reduction in wave activity received at the coast, increased sedimentation and beach formation, reduction of flood risk due to wave overtopping at the coast, reduction in sediment loss through rip-cell activity, formation of new "reef" ecosystems and increased biodiversity. Whereas the problems associated with offshore breakwaters are possible deflection and modification of longshore currents, high construction and maintenance costs, possible scour problems through gaps in segmented breakwaters and retention of sediment with corresponding increased erosion elsewhere along the coast. The usage of offshore breakwaters is recommended in: Coastal areas experiencing erosion because of wave activity and excessive sediment loss by shore normal currents, and where sediment build up would enhance coastal resilience.

4 Integrated and combined approaches

4.1 Integrated mitigation measures

Beside structures designed solely as mitigation measure against coastal erosion or tsunamis, they can also be integrated as part of infrastructure constructions. At the coast of Banda Aceh (Indonesia), it is proposed to construct a circuit road (Banda Aceh Outer Ring Road, BORR) intended to also act as tsunami mitigation measure (Syamsidik et al. 2019). During the 2004 IOT, the maximum tsunami height in Banda Aceh is estimated to be 15 m (Lavigne et al. 2009) and its impact resulted in a death toll of about 26,000 (Doocy et al. 2007). The BORR is planned to be constructed as an elevated road (3 m) as shown in Fig. 6 to act as a mitigation measure and shall be located behind the shoreline in Banda Aceh. Syamsidik et al. (2019) showed that the construction of the BORR may reduce the area of inundation by 8–22%, depending on the tsunami intensity, but also point to the possibility of damage (e.g. due to breaching) which needs to be examined further.

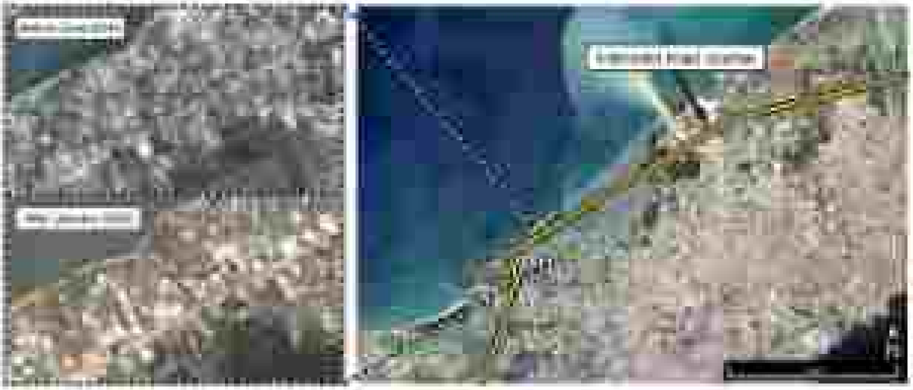

Fig. 6 Intended course of the elevated road in Banda Aceh. Left: Consequences of the 2004 IOT in Banda Aceh (Satellite data composite from Maxar Technologies accessed through Google Earth Pro, ver. 7.3.4.8248)

Samarasekara et al. (2017) discussed the reinforcement of an existing railway embankment as an additional tsunami countermeasure in the two coastal villages Dickwelleya and Wanawella in Sri Lanka. While they clearly found a tsunami-mitigating effect by enhancing the present rail embankments, the expected benefit (protected goods) seems to not compensate the anticipated costs.

4.2 Alternative approaches

4.2.1 Multi-layer approach

Several studies address multi-layer approaches (sometimes referred to as multi-layer safety) regarding tsunami impact mitigation (Fig. 7). This approach has received greater interest after the 2011 Tohoku Tsunami (Tsimopoulou et al. 2013; Samarasekara et al. 2017). Both studies referred to the *National Water Plan of the Netherlands 2009–2015*, which is explained in detail by Hoss et al. (2011). The Dutch multi-layer approach encompasses three main components:

- Layer 1 as prevention that encompasses all measures focusing on preventing floods (e.g. seawalls).
- Layer 2 as spatial solution addresses the spatial planning of areas and buildings in flood threatened areas.
- Layer 3 as emergency management that focuses on the hazard management in terms of hazard awareness among the population, evacuation plans or early-warning systems (Hoss et al. 2011; Esteban et al. 2013).

The application of multi-layer or prioritization of a particular layer depends on the region and country. In developing countries, single-mitigation measures are often preferred since they are economically more feasible. In developed countries on the other hand, more financial resources are available and, additionally, the assets at risk are economically more valuable. This leads to more comprehensive mitigation measures, for instance, in Japan (Esteban et al. 2013). In general, multi-layer approaches are considered as a parallel system instead of a serial system. This means, if one of the three layers fails, the remaining layers still provide mitigation (Jongejan et al. 2012; Tsimopoulou et al. 2013). However, in the case of tsunami mitigation, this is not entirely valid since a failure of Layer 1 (e.g. a seawall) may cause additional damage. Tsimopoulou et al. (2013) illustrated this by referring

Fig. 7 A schematic view of the multi-layer approach. Layer 1: Prevention (e.g. by offshore breakwaters or seawalls). Layer 2: Spatial planning (e.g. creating retention areas or lifted structures with porous structures). Layer 3: Management (e.g. evacuation plans, early warning systems) (modified and redrawn from Tsimopoulou et al. 2014, 2015)

to a dike-ring area in the Netherlands. If the probability of a failure of an evacuation plan (Layer 3) is higher than the possibility for a dike failure (Layer 1), the synergy between Layer 1 and Layer 3 diminishes and the costs for establishing the evacuation plan may surpass its expected benefits (Tsimopoulou et al. 2013). Furthermore, in the case of Layers 2 and 3 a threshold for the accepted damage in case of a hazard needs to be defined, determining the boundary conditions for these layers (e.g. minimum retreat from the coast; Layer 2) (Tsimopoulou et al. 2013).

In Tohoku region, a multi-layer mitigation approach already existed prior to the 2011 tsunami. However, it is not clear to what extent the approach was strategically planned and coordinated by local authorities or if it was implemented rather unintentionally/accidentally. In fact, the system failed in 2011 starting from the breakdown of most of the Level 1 measures (breakwaters, seawalls). On Layer 2, the early-warning system did respond and provided warning only three minutes after the earthquake, but the local emergency plans were not prepared for such an intense tsunami. Even some evacuation buildings were partially overtopped, while, in the low-lying areas people did not reach them in time (Tsimopoulou et al. 2013). Based on the analysis of Tsimopoulou et al. (2013) in Tohoku, it is recommended to elaborate risk-based multi-layer approaches based on damage and casualty thresholds determining the point of "failure" of a layer. Such an approach would provide additional protection in a multi-layer system. Furthermore, the authors emphasized the importance of tsunami awareness among the population for a functional multi-layer safety approach, based on a case study in the city of Rikuzentakata (Iwate Prefecture, Japan; Tsimopoulou et al. 2013).

4.2.2 Channels and dug pools

The Buckingham Canal along the city of Chennai situated along the southeast of India is a 30 m wide, 10 m deep and 310 km long channel flowing at a distance of 1 to 2 km parallel to the shoreline. In the area between Buckingham Canal and the shoreline, hamlets inhabited by several thousands of fishermen are located. During the 2004 IOT, the canal preserved elevated patches in this area from tsunami damage since the tsunami run-up approached and filled the canal at first, which then acted as an additional buffer zone (Rao 2005). The canal regulated the run-up back to the sea within 10 to 15 min. From this observation, Rao (2005) suggested investigating the influence of channels on tsunami run-up scientifically by considering further geomorphologic features and coastal inlets. Furthermore, Dao et al. (2013), Usman et al. (2014) and Rahman et al. (2017) investigated the application of channels and depressions as tsunami countermeasures both experimentally and numerically.

Dao et al. (2013) investigated the Kita-Teizan Canal in Sendai (Japan) numerically, which is assumed to have mitigated the impact of the 2011 Tohoku Tsunami significantly (Tokida and Tanimoto 2013). The Kita-Teizan Canal is a 9 km long canal running parallel to the shoreline at a distance of about 300 m to 400 m and is 40 m wide and 2 m deep. By several setups with and without the canal as well as different canal dimensions, the canal is found to be capable of reducing the tsunami energy significantly and its effectiveness would increase by greater width and depth. The canal effectiveness in terms of reducing tsunami overland flow velocity is reported to vary from about 16% to 20% during the 2011 Tohoku Tsunami. By applying fragility curves (Gokon et al. 2011) for structures, Dao et al.

(2013) furthermore assumed that the canal's contribution corresponds to a reduction of structural damage of 3–4%.

Rahman et al. (2017) studied different configurations of canal dimensions (width, depth) and additional countermeasures (dunes) for tsunami mitigation and identified a combined approach to be most promising. In general, the canal of largest dimensions (depth, width) showed the best mitigation performance. Flat but wide canals showed high wave reflections. However, all tested canals had a considerable mitigation effect in terms of reduced tsunami velocity and delayed tsunami flooding. Even though shore-parallel canals were capable to reduce the energy of the tsunami impact, there was no influence on inundation depth. The combination of sand dunes and a canal reduced both inundation depth and flow velocity (Rahman et al. 2017). Further studies on canal geometries as well as combinations of canals and traditional countermeasures for tsunami mitigation were suggested.

The mitigation function of canals, channels or dug pools was accidentally identified and also today such structures are not planned by intention. However, based on the experiences of the 2004 IOT and 2011 Tohoku Tsunami, the interest in understanding the associated hydrodynamic processes and elaborating quantifiable mitigation potentials of such structures is increasing.

4.2.3 Vertical evacuation

Structures for vertical evacuation could be considered both as hard and as soft tsunami countermeasures. However, in areas without natural high grounds as evacuation space, the construction of artificial structures is an option for shortening evacuation distances. These structures might further be divided into those originally designed as evacuation shelters or those constructed for other purposes (e.g. parking garages, hotels, etc.). However, if existing buildings are assigned as evacuation location, their stability against tsunami impact and the accessibility needs to be ensured (Goto and Yamori 2020). The construction of elevated or high grounds as evacuation sites is another option for designed vertical evacuation space. Such high grounds are suggested by the Federal Emergency Management Agency of the US (FEMA 2019) as comparably cost-effective structure for vertical evacuation compared to stand-alone structures or buildings. A provision of bottom clearance to the building by using continuous stilts was found to reduce the pressure impulse of the order of 20% to 30% through numerical and experimental investigations (Samarasiri and Yeh 2011). However, beyond a certain elevation extent, the clearance may not yield further reduction of the impact.

5 Future directions

5.1 Use of permeability

Mitigation structures of staggered non-continuous configurations lead to a reduction in the hydrostatic and hydrodynamic stresses during the initial wave impact, ongoing wave penetration and backflow. Recent research proves the linkage between hydrodynamic loads of tsunamis and the permeability of coastal structures, e.g. in terms of opened or closed windows. In all of these studies (e.g. Thusyanthan and Madabhushi 2008; Wilson et al. 2009; Lukkunaprasit et al. 2009; Triatmadja and Nurhasanah 2012), authors confirmed the effect of solid or elastic structures in combination with openings that permit free flow and provide energy dissipation. Lukkunaprasit et al. (2009), and independently Wilson et al. (2009), found that opening a structure of 25% and 50% reduces the hydrodynamic force by 15–25% and 30–40%, respectively. Such low or no-resistance mitigation measures (which are based on the idea of least resistance) should be based on openings in buildings as large as possible, or the implementation of weak and non stability supporting elements in the building in order to provide a calculated path for the flow that does not affect the stability of the building (ASCE 2017). An increase in the permeability of coastal buildings increases their stability, but the buildings will still be affected by flooding, and the final success is highly depending on the existing structure strength. Increasing the permeability of existing structures (e.g. open windows, doors, etc.) is a reasonable approach in order to mitigate the worst case and should be the last mitigation option since certain types of mid-term and long term damages (in particular regarding crucial infrastructure or flood-caused diseases) may not be prevented. For tsunami-prone areas, it is strongly recommended to leave sufficient space between ground level and the floor level of dwelling units. For critical installations, such as power plants, adequate caution should be taken by locating the sensitive components at high grounds to avoid any tsunami flooding.

5.2 Slowing by artificial elements (buffer blocks)

As explained in the previous paragraph, the use of permeability in tsunami mitigation measures is a promising approach. The main purpose of such constructions is to dissipate the impact energy and, therefore, also to reduce tsunami height. Permeable structures generate additional turbulences in the flow field, while they are not designed to resist the full wave impact energy. The dissipation results from the flow through the elements on both sides and over its top. Basically, the concept is comparable to the increased roughness provided by vegetation which is intensely studied (e.g. Shuto 1987; Kathiresan and Rajendran 2005, 2006; Olwig et al. 2007; Iverson and Prasad 2008; Tanaka 2007, 2010; Baird and Kerr 2008; Yanagisawa et al. 2009; Sundar et al. 2011; Noarayanan et al. 2012, 2013; Strusińska-Correia et al. 2013; Nateghi et al. 2016).

Until now, and related to mitigating storm surges, buffer blocks have been adopted as roughness elements over dikes and as space-saving reinforcement measure in existing dikes in order to enhance energy dissipation of overflow as shown in Fig. 8 (Oumeraci 2009; Hunt-Raby et al. 2010; EurOtop 2016).

Although such buffer blocks are not applied as countermeasure against tsunamis so far, their general applicability as tsunami mitigation measure is discussed by several authors (e.g. Oumeraci 2009; Thorenz and Blum 2011; Goseberg 2011, 2013; Rahman et al. 2014; Capel 2015). In his flume experiments, Goseberg (2011, 2013) showed that macro roughness elements have a significant effect on the run-up height of non-breaking

Fig. 8 View on small buffer blocks attached to coastal dikes (foreground) and large buffer blocks as mitigation measure against storm waves (photograph by Schüttrumpf, 2003)

long waves mainly depending on element configuration (aligned, staggered) and wave direction. Goseberg (2011, 2013) focussed on the run-up reduction due to the presence of macro-roughness elements as buildings (referred to as coastal urban settlements), which are not fully submerged during the run-up, but did not consider the force reduction behind the macro-roughness elements (Fig. 9). The run-up reduction was mainly addressed towards momentum exchanges within the wave during the overflow of the macro-roughness elements, leading to the generation of higher turbulences. These preliminary findings support the use of buffer blocks for tsunami mitigation (Goseberg 2011, 2013). Similarly, Giridhar and Mani Reddy (2015) investigated the effect of different shapes of buffer blocks (rectangular, semi-circular, trapezoidal) installed over sloped structures to assess their effectiveness in the reduction of wave run-up and reflection. Rahman et al. (2014, 2017) investigated the performance of continuous seawalls of two different heights and one perforated seawall regarding wave impact attenuation. A dam-break setup and a load cell for investigating the bore impact were used. The load cell was installed behind the seawall to gain insights into the mitigation characteristics of these structures (Fig. 9). For continuous seawalls, the performance of higher seawalls built closer to a structure of interest led to the highest impact-force reduction on the structure of interest. Nevertheless, the perforated seawall exhibited a reduction in wave height and force of about 33% compared to no protection. Furthermore, the perforated seawall allows overtopping and backflow into the sea, resulting in decreased forces acting on nearby structures. The perforated seawall had the same total height as the continuous sea wall (8 cm) but is divided into a lower continuous section (3.8 cm height) and an upper discontinuous section (elements of 4.2 cm height). This results in material savings to an extent of about 25% with good attenuation characteristics.

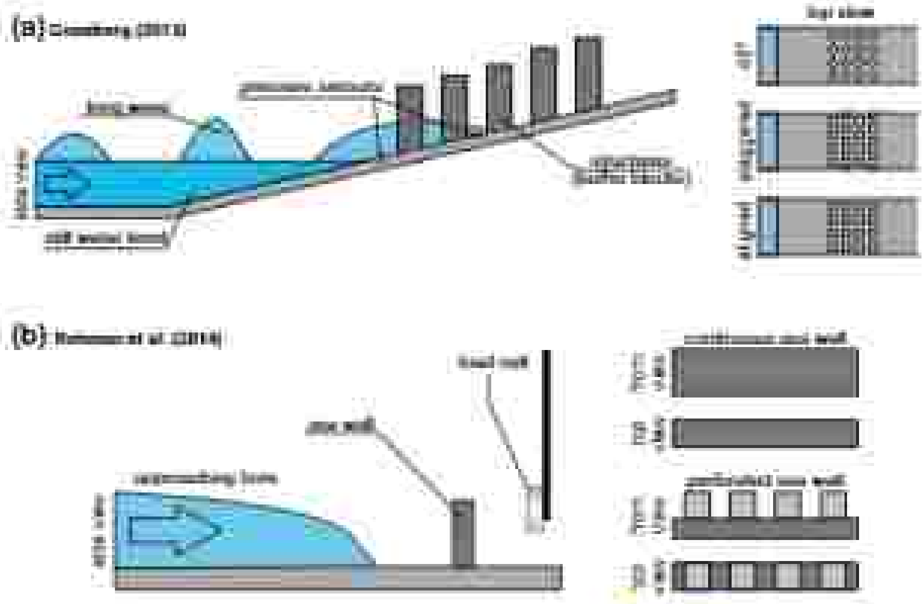

Fig. 9 Simplified sketch of the laboratory experiments of Goseberg (2011, 2013, redrawn) and Rahman et al. (2014, redrawn). Goseberg (2013) shows that buffer elements can reduce the run-up significantly. In Rahman et al. (2014) the continuous seawall leads to a force reduction of 41% in the experiments, while the perforated seawall reduces the impact force by 33% of the case without any protection of the load cell.

5.3 Recurved seawalls

Recurved seawalls (also recurved parapet walls) or breakwaters are occasionally applied as storm-wave countermeasures (Fig. 10). Their application as tsunami countermeasures is not common and, to the best knowledge of the authors, no publication addressing tsunamis is available beside a patent application of Igawa (2012, Fig. 10c).

Anand et al. (2011) compared the hydrodynamic characteristics of seawall profiles and found the lowest reflections for circular cum parabola shapes (CPS) followed by Galveston wall shapes (GS). The CPS shape mentioned in the patent of Weber (1934) consists of a smooth parabola to gently guide the incoming waves to the quadrant circle at the top that redirects the waves back to the seaside. The Galveston wall shape (GS) consisting of two radii of curvature has been earlier adopted as a seawall at Galveston, Texas, USA (Anand et al. 2011).

Molines et al. (2019, 2020) investigated mound breakwaters reinforced with parapet walls regarding wave forces by flume experiments and numerical simulations using OpenFOAM. They have reported that the horizontal wave forces increase by a factor of 2 compared to standard vertical wall breakwaters. However, they showed that curved crowns are able to reduce wave overtopping significantly until the impact discharge is too high. Then, no further significant influence of the curved parapet on wave overtopping was observed.

Castellino et al. (2018) conducted two-dimensional numerical investigations on the interactions between curved seawalls and impulsive forces. It was shown that the hydrodynamic pressures due to non-breaking waves increase significantly on a larger portion of the fully submerged recurved parapet wall. A high influence on the impact forces is attributed to the opening angle of the curve. Investigations on the correlation between wave period and wave impact on the curved seawall crest show that the wave load increases with wave steepness (Castellino et al. 2018).

Martinelli et al. (2018) investigated the loads of non-breaking waves on a recurved parapet with different exit angles. They reported "partially recurved parapets" with exit angles of 60° to be a good compromise between the reduction of forces and overtopping. Ravindar et al. (2019) studied the characteristics of wave impact on vertical walls with recurve in large scale and analyse the variation of impact pressure. Stagonas et al. (2020) compared the impact forces on three types of recurves based on large-scale experiments and found that the mean of the largest peak force increases with an increasing angle of curvature. Recently, Ravindar and Sriram (2021) reported on the influence of three recurved and plain parapets on the top of vertical walls. It was concluded that large parapets seem to be more effective in the reduction of forces for higher waves compared to other parapet types.

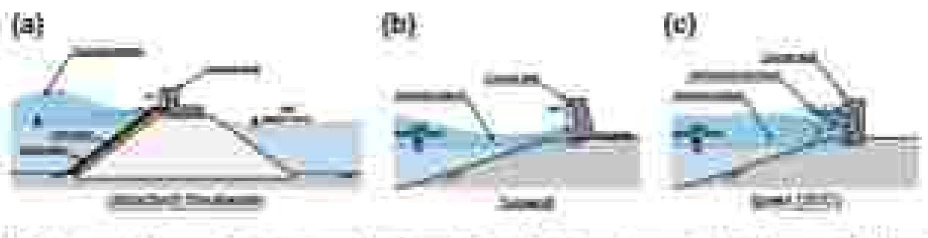

Fig. 10 Recurved seawalls on a mound breakwater (a) and as a coastal seawall (b). c Approach of Igawa (2012) which aims at more controlled flow redirection

5.4 Large tsunami barrier

Scheel (2014a, b, c) proposed a novel tsunami countermeasure based on shoaling processes and preventing steepening of waves in the nearshore (Fig. 11). The idea is based on reflecting the wave motion by a submerged vertical wall in front of the shoreline. The vertical wall needs to be placed up to several tens of kilometers offshore at a depth between 20 and 200 m (Scheel 2014b) or 50 m and 300 m (Scheel 2014a), respectively. The crest is equipped with an extending wall of 6 m to 8 m on top of the vertical wall. To avoid wave reflections, Scheel (2014a, b, c) suggested a slight inclination in the wall, irregular shapes or optimized surface roughness for introducing wave distraction in the reflected wave. Scheel (2014a, b, c) acknowledged the large financial and material demands of this measure and proposed to reclaim the space between wall and shoreline as additional land. This type of measure could be considered for protecting crucial installations that cannot easily be protected or relocated, or which pose a hazard themselves in the event of a collapse, such as nuclear power plants. However, scour could be a serious problem if not properly addressed. As another option, Scheel (2014a, b, c)

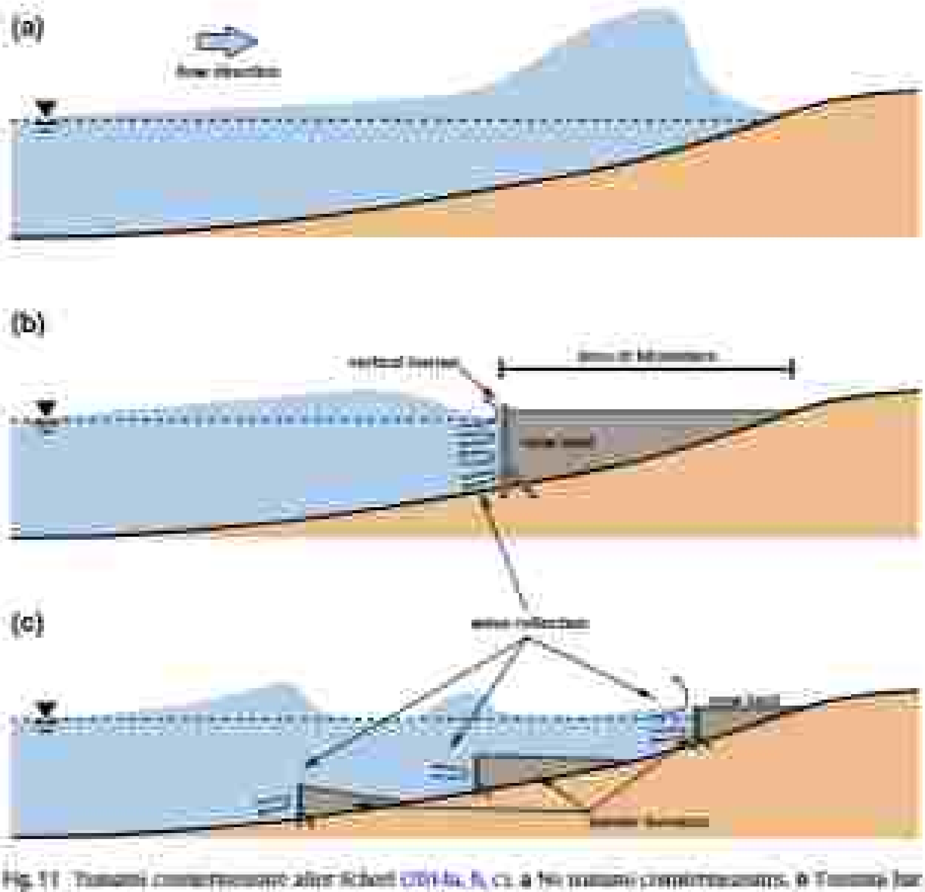

Fig. 11 Tsunami countermeasures after Scheel (2014a, b, c). a No tsunami countermeasures. b Tsunami barrier in large distance to the high-tide line (dashed line). c Fragmentation of the barrier into several sub-terraces in order to save material and costs (redrawn and extended after Scheel 2014a, b, c)

recommended constructing not one single deep vertical wall but to implement several smaller walls for reducing the costs (Fig. 11c).

Furthermore, Scheel (2014b) suggested combining the tsunami countermeasure with hydro-power plants. Here, the vertical wall would be equipped with turbines driven by the tidal current. Alternatively, the space between the vertical walls is proposed to be used for fish farming (Scheel 2014a, b, c). A numerical study by Elsafti et al. (2017) revealed that such a barrier is effective in reducing the tsunami energy significantly before reaching the shoreline. However, at the wall, the run-up height increases more than twice the height of the approaching tsunami, and the influence of the face-roughness of the barrier has only minor influence on wave run-up and reflection. The approach of Scheel (2014a, b, c) seems to have not been validated or tested physically so far. Furthermore, the construction of such countermeasures would require substantial fundamental research not only on the hydrodynamic characteristics and design but also on the construction sequence and procedure, which might require further innovations (Scheel 2014b). A further adverse effect would be imposed on the ecology of shallow marine environments around and behind these barriers.

6 Discussion

The review revealed that a range of hard countermeasures for mitigating tsunami impact exist, but that they also need a critical evaluation prior to installation. In most cases, the local environmental, social and financial factors determine the technique to be adopted. Hard structural measures like dykes, seawalls or breakwaters have high construction costs and can provide a false feeling of security which might even increase the structural damage and fatalities if they fail during tsunami impact. Due to the known disadvantages of seawalls and dykes (Sect. 3.3), further developments in the field of structural tsunami countermeasures are necessary, some of which are summarized in Table 3.

Despite breakwaters and seawalls do have disadvantages, a re-design of such structures (e.g. by raising their crest elevation or applying recurved parapets) can, at least marginally, increase their efficacy during the tsunami ingress. On the other hand, physical and numerical investigations show that hydrodynamic forces acting on the walls increase significantly due to the recurved parapet. Based on the high hydrodynamic energy of tsunamis, it is questionable how reliable such recurved seawalls in dimensions sufficiently high for large tsunamis would be (i.e. if they are reasonable applicable for Level 2 tsunamis). Furthermore, this would involve a huge financial investment; a decision would depend on the local frequency–magnitude pattern of tsunamis, the value of assets, as outlined by Stein and Stein (2013), and of course the vulnerability of the coastal population. In any case should their dimensions be large enough to reduce the tsunami inundation levels. However, with regard to the perennial problems of coastal erosion, today's breakwaters and seawalls may serve their purpose.

The application of artificial slowing elements (buffer blocks) could be effective as they are easier to install and can serve as buffers in reducing the tsunami inundation. Their general applicability is already proven against storm waves along the coast of Norderney Island, Germany (Schüttrumpf et al. 2002). Such buffer blocks might also be highly useful as (supportive) countermeasure for tsunamis if their dimensions are derived from detailed scientific investigations. Extended investigations are also necessary to determine whether the buffer block approach may also be suitable for Level 2 tsunamis.

Table 3 Overview on selected advanced structural tsunami countermeasures

	Buffer blocks	Controlled permeability	Integrated measures	Multi-layer approaches	Recurved seawall	Tsunami barrier after [illegible]
Description	Energy dissipation by artificial, disconnected rigid structures	Reducing the hydrodynamic force by enabling free pathways for the flow (e.g. through buildings)	Utilisation of natural or artificial topographic features (e.g. dug pools, soil embankments)	Combination of multiple classical or advanced approaches (e.g. seawalls and integrated measures)	Modification of classical seawall approaches, generating wave deflection/energy reflection	Artificial creation of large, submerged elements for wave and energy reflection
Known applications	Several applications for storm waves/high waves	Not relevant	Case of Banda Aceh (Indonesia)	National Water Plan of the Netherlands 2009–2015 (storm waves)	Several applications for storm waves	Not relevant
Targeted tsunami level	Level 1, Level 2*	Level 1	Level 1, Level 2*	Level 1, Level 2*	Level 1, Level 2*	Level 1, Level 2
Intended level of protection	Mitigation of wave impact forces and reduction of the inundation extent	Mitigation of wave impact	Prevention or mitigation of wave impact and reduction of the inundation extent	Prevention or mitigation of wave impact and inundation extent, providing evacuation time	Prevention of wave impact	Prevention or mitigation of wave impact and reduction of the inundation extent
Financial effort	Manageable	Low	Low to high	High	High	Very high
Character of protection measure/required construction space	Developed	Not developed or in development	Developed	Developed	Developed	Developed
Literature (example)	Oumeraci (2009), Goseberg (2011)	Lukkunaprasit et al. (2009), Wüthrich et al. (2009)	Synolakis et al. (2019)	Tsimopoulou et al. (2013)	Iguwa (2013)	[illegible] (2014a, b, c)

*Qualification or limited applicability

Recently integrated tsunami mitigation measures are considered as a practical solution. The reinforcement of existing or construction of combined structures might be a useful alternative especially in regions where financial resources for countermeasures are limited. Especially elevated roads or railway embankments can be suitable options, as in the case of Banda Aceh. Channels and dug pools might also be considered as further integrated mitigation measures. Recent investigations show that channels and topographic depressions are capable to mitigate tsunami run-up and, depending on their arrangement, to steer the backflow to the open sea in a more controlled way. The application of such integrated countermeasures needs to be investigated further and more systematically in terms of sufficient dimensions, integration into the coastal ecosystems and tourism, and economic questions. Nevertheless, the application of channels/topographic depressions would always divide the coastal area into a more and less protected part. Therefore, their application might be combined with a first defence line of breakwaters, seawalls, buffer blocks or vegetation belts. The separation of the coastal area into more and less protected parts, needs to be combined with specifically adapted land use in the flood-prone areas.

The combination of topographic depressions and hard structural countermeasures results in multi-layer approaches. If Layer 1 (e.g. seawalls) fails, Layer 2 (e.g. topographic depressions) will still provide attenuation. However, the failure of the first defence line would lead to additional damage in the area between seawall and depression, while Layer 2 (topographic depression) would prevent areas on its lee side from higher damages. Herein, Layer 3 (emergency management) would act in combination with Layer 2 since the functionality of Layer 2 would highly depend on timely evacuation of the area between Layer 1 (seawall) and 2 (depression). However, as stated by Tsimopoulou et al. (2013), the Dutch multi-layer approach has to be adjusted in order to be suitable for combating other types of high-energy wave impacts such as tsunamis. A great deal of research on this topic is recommended since none of the presented mitigation measures can serve as an overall valid and completely successful mitigation technique on its own. Furthermore, multi-layer approaches can also be a promising option regarding Level 2 tsunamis if Layers 1 and 2 are considered as "failable" layers which provide additional time for evacuation.

Completely novel approaches of tsunami countermeasures are rare, which might be due to the complexity of the hydrodynamic processes and the low predictability of tsunami occurrence and intensity. Connected to the unpredictability of tsunamis, test applications of novel approaches are not easy to implement. Test areas need to be selected carefully. Whether the selected area will be affected by a tsunami within a manageable period is not predictable. On the other hand, if the effectiveness of such measures cannot be fully proven by numerical or experimental investigations, a remnant risk is associated to the application in populated areas. This might hamper the development and implementation of new approaches.

As stated earlier, a novel tsunami barrier which is based on the idea of preventing a tsunami from shoaling and reducing its impact energy and run-up was proposed by Scheel (2014a, b, c) and Elsafti et al. (2017). It is at concept stage and substantial research through experimental and numerical investigations as well as trials in the field are required to prove its efficacy. A large amount of economic, material and labour resources would be needed for the construction and the (most probably very high) ecological impact is undeterminable.

The available literature mainly concentrates on failed countermeasures. Naturally, existing and successful countermeasures do not receive as much attention. Therefore, we encourage to include also successful tsunami countermeasures in future research studies in order to raise datasets showing dependencies between countermeasure type, design and dimensions, and the tsunami impact. Such data would enable authorities and other persons in charge at affected coasts to better evaluate their hazard management. Furthermore, such reviews would highly benefit from preferably comprehensive datasets encompassing data for the tsunami intensity and properties, countermeasure design (dimensions, material, vegetation type, soil type, etc.) and coastal topography and bathymetry. Elaborating such datasets and corresponding correlations would help to increase the planning security at threatened coasts.

As further support to tsunami mitigation, researchers started to utilise tsunami deposits for reconstructing the energy of palaeotsunamis, over the last three decades (Etienne et al. 2011; Engel and May 2012; Vött et al. 2013; Sugawara et al. 2014; Costa and Andrade 2020; Oetjen et al. 2020). Knowledge on palaeotsunamis can help to successfully improve regional specific tsunami countermeasure programmes since they allow to extend the scale of known events to several thousands of years and lead, subsequently, to an increased preparedness and awareness of possible tsunami events and their energy and flooding potential.

This review shows that tsunami mitigation measures are a broad research field of high interest. Recent destructive tsunamis intensified the research interest further since tsunami hazards can result in enormous damages and fatalities. Past tsunamis show that it is dangerous to base tsunami mitigation on only one layer since its failure highly likely results in disastrous hazards. For establishing new approaches and enhancing existing countermeasures, broad datasets can support researchers in adjusting mitigation measures to specific regional areas, e.g. in terms of land use and topography and expectable tsunami impacts. This requires close collaborations between different scientific disciplines (e.g. engineers, geologists, geographers, sociologists) since knowledge on construction, seismology, palaeotsunamis, and regional social-economic and cultural properties highly determine the success of local mitigation measures and connected management plans.

Regarding the hard countermeasures only, a combination of blocking (e.g. seawalls), slowing (e.g. vegetation, buffer blocks) and steering structures (e.g. channels, topographic depressions) that considers long-term tsunami hazard, people and assets at risk, financial resources and the coastal configuration at a local scale is considered most promising. However, it should always be considered that tsunami mitigation measures as a whole can never provide a safety level of 100%, as there is an upper limit of mitigation investment depending on the assets at risk (Stein and Stein 2013) and the magnitude of future tsunamis is still difficult to assess.

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Declarations

Conflicts of interest The authors declare no conflict of interest.

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