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Combination of school evacuation drill with tsunami inundation simulation: Consensus-making between disaster experts and citizens on an evacuation strategy

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ABSTRACT

This paper aims to introduce an effective methodology for communicating a science-based tsunami risk scenario to non-expert citizens through consensus-making between disaster experts and non-experts, with the aid of four-way split-screen movie clips depicting evacuation scenarios. Action research on tsunami education in Zihuatanejo, Mexico found that a perception of tsunamis as catastrophic together with the one-directional nature of risk communication resulted in inaction on the part of non-experts in disaster preparedness, contrary to the expectations of experts. In other words, non-experts did not think that they could cope with a tsunami disaster and they perceived that as non-experts they themselves could not affect the tsunami risk scenario communicated to them by the experts. In response, movie clips simultaneously displaying a school evacuation drill and tsunami inundation simulation were developed. These movie clips are intended to serve as a tool in the process of establishing a school tsunami evacuation strategy by promoting consensus-making between experts and non-experts about the risk scenario, thereby helping to change the perception of a tsunami from a catastrophe that cannot be dealt with by non-experts to a realistic perception that non-experts can indeed help by engaging in their own tsunami risk preparedness activities. The developed movie clips were used at a workshop for stakeholders, including academics, local government, and teachers, with the aims of establishing scenario-based evacuation strategies and promoting the proactive implementation of preparedness activities by non-expert teachers. The study will contribute to establishing a mechanism for applying scientific knowledge to solving societal issues.

1. Introduction

Communicating evidence-based disaster related-knowledge is widely considered to increase people's risk perception, leading them to proactively take preparedness action and respond appropriately during natural disasters [1–6]. Against this background, one of the important roles of research is to communicate disaster-related scientific knowledge to facilitate risk-reduction actions and prevent loss of life. The international agenda of the Sendai Framework for Disaster Risk Reduction [7] also calls for academia to apply scientific disaster knowledge to support science-based decision-making for risk reduction. Under the Science and Technology Roadmap [8], academia and other stakeholders agreed to support the implementation of the Sendai Framework to promote interdisciplinary scientific collaboration and multi-stakeholder partnerships among researchers, policymakers, communities, and the education sector to make scientific knowledge accessible to society. Therefore, a method for communicating scientific knowledge, particularly how to communicate the uncertainty and probability of low-frequency natural disasters, is an area of interest for researchers and practitioners [9–11].

However, communicating risks does not always lead to people taking risk reduction countermeasures and engaging in appropriate evacuation behavior, contrary to the perception–proactive action framework. This has been termed the "risk perception paradox" [12]. For example, in a study of communities living close to an active volcano in New Zealand, experts communicated the high potential risk of disaster from a low-probability eruption, and non-experts recognized the potential disruptive consequences of an eruption but were nevertheless willing to

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live in the area to enjoy its scenic beauty [13]. Tsunami disaster education has been confirmed as effective for enhancing tsunami risk perception. A study conducted in Acapulco, Mexico found that high school students there were more interested in learning information than in learning appropriate actions to protect their lives, which also implies a missing link between the perception of risk and taking proactive action [14]. Wechinger et al. [12] analyzes the factors of the missing link based on a review of 35 papers on risk perception related to different natural disasters. As a result, three factors were identified: first, individuals choose to accept the risk because the benefits of living in an area prone to natural disasters are greater than the risk; second, the risk is recognized by the individuals, but taking countermeasures is considered the responsibility of government agencies or experts; third, the individuals recognize the risk but cannot relocate because they have limited resources.

The following is an example of how increased risk perception can be an impediment to people taking action. The Cabinet Office of Japan presented the updated worst-case scenario for Nankai megathrust earthquakes in 2012 [47]. The prediction reported that a 10-m-high tsunami could be observed in 23 municipalities, the tsunami could reach 34 m high in the town of Kuroshio in Kochi Prefecture, Japan, and that the total fatalities in Japan could be as high as 323,000 people. Through an intensive field survey, Sun et al. [15] identified three types of negative attitudes held by people in Kuroshio arising from the catastrophic worst-case scenario. They were “overly pessimistic,” where people thought that any tsunami risk preparedness was meaningless; “overly optimistic,” where people did not believe that such a big tsunami could happen; and “overly dependent,” where people thought that only disaster experts could deal with the tsunami and non-experts, such as ordinary citizens, could only depend on the experts. As a result of these attitudes, non-experts in Kuroshio became reluctant to engage in tsunami risk preparedness, such as making evacuation strategies, attending tsunami evacuation drills, and preparing emergency food and supplies (e.g., Refs. [15–18]. These negative attitudes implied that even though they had an increased perception of the tsunami risk, the non-experts did not think they could cope with a tsunami disaster and perceived that, as non-experts, they themselves could not change the tsunami scenario.

As seen in the above example, the risk perception–proactive action framework does not necessarily function as intended, and risk communication from expert to non-expert carries with it the possibility of disincentivizing people from preparing for the natural disasters. So, how can this gap between risk perception and action can be closed? Previous studies indicate that the gap is the result of a lack of trust among non-expert citizens, scientific experts, and government institutions. Based on an intensive literature review of mostly European-based papers, Wachinger [12] concluded that distrust is the key factor in creating the gap, rather than other cultural and individual factors. Thus, participation of non-expert citizens in the process of risk assessment was suggested. Brofman et al. [19] conducted a questionnaire survey of 2054 citizens living with the risk of natural disasters, including earthquakes and tsunamis, in Chile and found that distrust of the government impeded preparedness. Thus, building trust with government authorities and the scientific community, which plays a role in communicating risk, is suggested to promote preparedness among citizens. Based on experiences in Japan, Yamori [20] also suggests that the key to engendering a more proactive attitude among non-experts is a consensus-making process in which experts and non-experts hold a mutual dialogue for the purpose of understanding the experts’ risk scenario, and reaching consensus on the idea that tsunami risk preparedness can affect the risk scenario and reduce damage in the event of an actual disaster. Thus, by building trust and reaching consensus among non-expert citizens, disaster experts, and government institutions, the attitudes of non-experts can be positively affected such that people implement tsunami risk preparedness.

This study describes a mutual consensus-making process between experts and non-experts to establish a school tsunami evacuation strategy through tsunami education, evacuation drills, and workshops in Zihuatanejo de Azueta, Guerrero, Mexico. The term ‘experts’ in the following discussion refers to the authors from academia and local government Civil Protection officers. ‘Non-experts’ refers to citizens, students, and teachers. First, the paper introduces the action research on tsunami education provided by the first author to a total of 10,031 students, teachers, and citizens in Zihuatanejo over 291 days.

Second, the educational practices identified the following three major problems that result in reduced tsunami risk preparedness. The first problem was the strong perception of tsunamis as catastrophic held by citizens in Zihuatanejo, similar to Kuroshio, that made them feel powerless and that tsunami preparedness and evacuation drills were useless. In other words, the citizens thought that they could not deal with a tsunami. The second problem was the one-directional education structure, in which experts communicate knowledge to non-experts, which results in the lack of consensus-making among stakeholders that has a combined negative effect with the negative perception of tsunamis. The third problem was the lack of basic knowledge about earthquakes and tsunamis, which was related to the history of the study area.

Third, the development and application of four-way split-screen evacuation drill movie clips are described. The movie clips are embedded into the article as playable videos. This tool displays the evacuation behavior and tsunami inundation simulation simultaneously, which communicates the experts’ risk scenario based on tsunami inundation simulations integrated with the non-expert perspective of local school teachers based on the school evacuation drill. The tool is intended to establish a school tsunami evacuation strategy by promoting consensus-making between the experts and non-experts about the risk scenario, thereby helping to change the perception of a tsunami from a catastrophe that can be dealt with by only the experts to a realistic perception that non-experts can also help through their own tsunami risk preparedness activities.

The study demonstrates that a process of consensus-making between experts and non-experts can promote a proactive attitude among non-experts, leading them to implement risk preparedness activities. Furthermore, our observations will contribute to establishing a mechanism for applying scientific knowledge to society.

2. Action research in Zihuatanejo

Zihuatanejo de Azueta municipality is located in the northwestern state of Guerrero, Mexico (dot in the upper right map of Fig. 1). The municipality has a population of about 125,000 [21]. The area consists of an urban zone in the southwest, facing the Pacific Ocean, and a rural mountainous zone in the northeast. Fig. 1 shows an enlarged map of the urban zone of Zihuatanejo, which is referred to as Zihuatanejo hereafter. All the important infrastructure, such as schools, banks, municipal markets, hospitals, and hotels, are concentrated in the lowland less than 5 m above sea level. Guerrero, including Zihuatanejo, could be affected by earthquakes and tsunamis because the subduction zone along its coast has a section that has not liberated a deformation with magnitude 7.0 or higher for more than 100 years, which is known as the Guerrero seismic gap [22]. Thus, the risk of an earthquake and tsunami is high.

In action research, researchers collaborate with locals to tackle problems. Therefore, the intervention of the researchers in the field and the intention to help the targeted locality are integral to the philosophy of action research (e.g., Ref. [23,24]. The tsunami education intervention by the first author in Zihuatanejo started from September 2016 as part of the project “Hazard Assessment of Large Earthquakes and Tsunamis in the Mexican Pacific Coast for Disaster Mitigation,” jointly launched by Kyoto University, Japan, National Autonomous University of Mexico, Mexico, and the Mexican National Disaster Prevention Center. The first author discussed current issues in Zihuatanejo with the Civil Protection officers and agreed to work together on tsunami

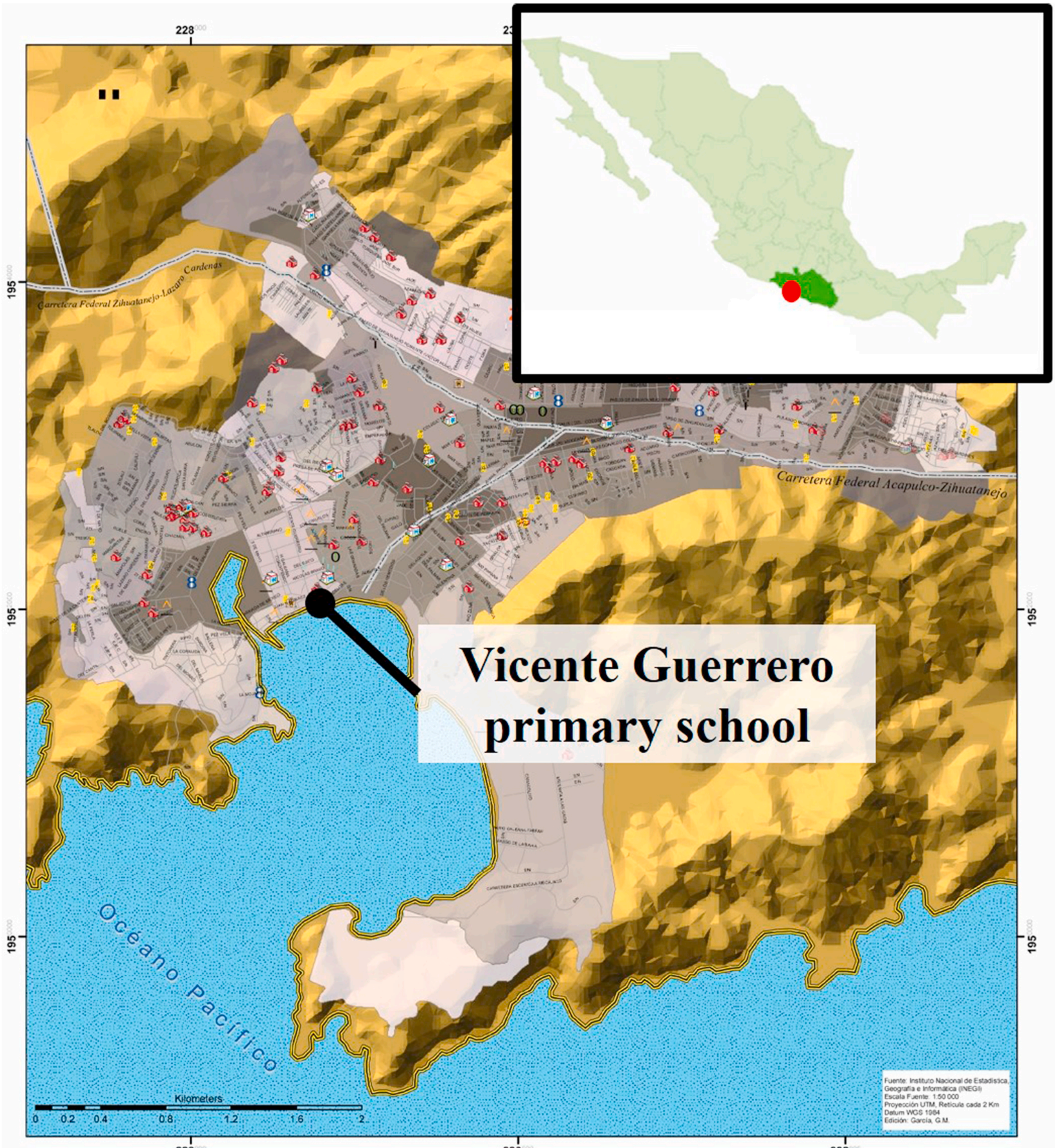

Fig. 1. Location of the study area.

education and evacuation drills at schools.

The first author planned and carried out tsunami education at schools in collaboration with the Civil Protection officers over a total of 291 days in Zihuatanejo between September 2016 and November 2019. Tsunami education, including evacuation drills, was carried out 82 times in three kindergartens, five primary schools, four secondary schools, four high schools, and three communities, reaching 6625 students, 446 teachers, and 2960 adults. A variety of educational content was used, such as lectures about the mechanism of tsunamis and knowledge about preparedness, workshops to identify evacuation routes and make maps with students, earthquake and tsunami evacuation drills, sharing experiences of earthquakes and tsunamis in Zihuatanejo, development of the culturally tuned card game, earthquake science education using a waveform recorded by a seismometer, establishment of a student committee for civil protection, and a community disaster management team.

Here, we focus on Vicente Guerrero Primary School (Fig. 1), which has approximately 400 students and is located in the middle of the Zihuatanejo lowland only 30 m from the bay shoreline. The school comprises a pair of two-story buildings. The school's evacuation plan

Table 1
Tsunami education activities held in Vicente Guerrero Primary School.

No.	Date	Target	Educational contents
1	28 Sep 16	17 teachers	Lecture on earthquake and tsunami mechanism
2	4 Oct 16	135 students	Lecture on earthquake and tsunami mechanism Card game to learn adequate response in disasters
3	5 Oct 16	146 students	Lecture on earthquake and tsunami mechanism Card game to learn adequate response in disasters
4	7 Oct 16	14 teachers	Workshop to design the evacuation route
5	14 Oct 16	300 students and 20 teachers	Tsunami evacuation drill
6	25 Mar 17	300 students and 27 teachers	Tsunami evacuation drill
7	6 Jul 17	123 students	Lecture on earthquake and tsunami mechanism
8	16 Nov 17	14 teachers	Sharing of preliminary results of tsunami inundation simulation in Zihuatanejo
9	22 Nov 17	150 parents	Lecture on earthquake and tsunami mechanism Sharing of the school evacuation strategy
10	24 Oct 18	14 teachers	Sharing of preliminary results of tsunami inundation simulation in Zihuatanejo
11	6 Jun 19	16 teachers	Sharing of four-way split-screen evacuation movie clips and workshop for tsunami evacuation strategy
12	19 Nov 19	330 students and 21 teachers	Evacuation drill to the second floor of the school Discussion

includes traveling at least 1 km to reach elevated land. The series of tsunami disaster education and drills provided by the Civil Protection officers and the first author are listed in Table 1. The intervention can be divided into three phases. In the first phase, basic knowledge was shared about earthquake and tsunami risks in Zihuatanejo and the tsunami evacuation drill was practiced (Nos. 1–5 in Table 1). In the second phase, evacuation movie clips were developed with all stakeholders, which was also an important process in sharing the preliminary results of the probable tsunami height and inundation zone in Zihuatanejo (Nos. 6–10). In the third phase, the evacuation movie clips were shown and mutual consensus about the risk scenario was sought to revise the evacuation strategies in Vicente Guerrero Primary sSchool (Nos. 11 and 12). The problems found by the action research are described in Section 3, followed by a detailed explanation of each phase.

3. Problems

3.1. Catastrophic perceptions of tsunamis

Zihuatanejo experienced 49 tsunamis between 1732 and 1985 [25]. The most recent large tsunami in Zihuatanejo was recorded following the 1925 earthquake with a magnitude of 7 and reached 7–11 m high in Zihuatanejo Bay [26]. Tsunami evacuation advisories have been issued relatively frequently in Zihuatanejo; for example, after the Chile earthquake in 2010, the Great East Japan Earthquake and Tsunami in 2011, and the Chiapas earthquake in 2017. Furthermore, the tsunami assessment project calculated the potential maximum tsunami run-up with low probability as 7.9 m in Zihuatanejo.

Regardless of these previous tsunamis and the tsunami height estimation, people in Zihuatanejo had unrealistic catastrophic perceptions of tsunamis. The first author and Civil Protection officers gave many lectures on earthquake and tsunami mechanisms to students and teachers in different schools, and the first reaction to the lectures was frequently expressed in comments such as "I will be killed by a tsunami" and "there is no place for evacuation." In an extreme case, a secondary school student started to cry due to their fear of tsunamis. These statements demotivate students and teachers from working on tsunami countermeasures, preventing the Civil Protection officers and authors from continuing educational interventions. Consequently, tsunami risk preparedness actions are not taken.

Further evidence about the effect of catastrophic perceptions of tsunamis was gathered through a paper-based questionnaire survey conducted in November 2017 with 586 secondary school students from three schools located in the possible tsunami inundation zone and their 231 parents. The question was "What is the maximum height in meters that you think a tsunami reaches in Zihuatanejo?" (in Spanish, "¿Cuál es el máximo de metros de altura que usted piensa que puede alcanzar un tsunami en Zihuatanejo?"). The question was open-ended so that the respondents could answer with any number. The answers were classified as shown in Table 2. Even though the 1925 tsunami in Zihuatanejo reached around 10 m, 68.3% of the students thought that a tsunami more than 11 m high was possible. More importantly, 18.3% of students thought that a tsunami 31–100 m high could hit Zihuatanejo and 12.1% thought that the tsunami height could exceed 101 m. In the survey results for parents, 52.4% of respondents thought that the tsunami could exceed 11 m high. Even though this was a smaller percentage than the students, a certain percentage of parents also had an extraordinary idea of the height of a tsunami; 8.7% of parents thought that the tsunami could be 31–100 m and 5.6% thought more than 101 m high. The survey results demonstrate the beliefs about possible tsunami height held by citizens in Zihuatanejo.

The catastrophic perception of tsunamis in Zihuatanejo is also observed in paintings made by students. The Civil Protection officers and the first author organized a painting contest in 2018 commemorating United Nations World Tsunami Awareness Day. The contest was called "Learning disaster prevention! Recognize the hazard and take action!" (in Spanish: "Aprendamos a prevenir desastres! Reconoce el peligro y ponte en accion!"), the main objective of which was to have students think of and paint risk reduction measures to survive an earthquake and tsunami. In total, 305 students participated in the pre-primary, primary, secondary, and high school categories. The paintings tended to show the devastation of high-rise buildings and the use of helicopters for evacuation (Fig. 2). Thus, the children assumed that the buildings were not high enough for evacuation, and rescue by helicopter was required to survive a tsunami.

Scientific studies and historical antecedents indicated that the maximum tsunami height is around 10 m; however, the perception that citizens have is quite different. The catastrophic perception of a tsunami makes people in Zihuatanejo feel powerless and consider working on tsunami preparedness and evacuation drills as useless. In other words, non-experts perceive tsunamis as a disaster that they cannot cope with

Table 2
Tsunami height estimated by students and parents.

Tsunami height (m)	Percentage of students	Percentage of parents
0–5	13.7%	15.6%
6–10	18.1%	32.0%
11–20	23.9%	27.3%
21–30	14.0%	10.8%
31–100	18.3%	8.7%
More than 101	12.1%	5.6%
Total	100.0%	100.0%

Fig. 2. Tsunami painting by a primary school 6th grader.

or that is out of their control. In contrast, experts know based on scientific data and historical antecedents that tsunami countermeasures and an educational approach are useful, and the measures taken by citizens can cope with tsunamis. Thus, the catastrophic perception of tsunamis held by citizens must be changed to promote risk preparedness in Zihuatanejo through the consensus-making.

3.2. Problematic active instructor/passive learner education structure

Previous studies, such as Yamori [20]; Wachinger [12]; Feldeman et al. [27]; Brofman et al. [19]; Howard et al. [28]; Lejano et al. [29]; and Lee and Yamori [30]; have pointed out that the one-directional nature of disaster education causes citizens to distrust experts and government institutions and turns learners into passive followers of educational messages, thus depriving individuals of their capacity to make their own decisions. Thus, a democratic approach to consensus-making among stakeholders has been suggested for risk communication.

The mechanism for inducing passivity has been explained in the educational psychology literature [31]. In general, education has a basic structure in which an instructor teaches a learner. Knowledge and skills are transferred from instructor to learner, expecting that the learner applies the knowledge and skills they acquire. However, this fundamental education structure has the following pitfall in its educational principle [31]. The structure places the instructor in an active/-authoritative role relative to the learner who assumes the role of a passive/subordinate actor. Hence, contrary to the instructor's expectation of the learner's application of their learnt knowledge and skills, the learner adopts a passive attitude. Once the structure is established, the learner is accustomed to passively following the instructor's instructions.

Considering this structure in the context of disaster education and risk communication, the expert/non-expert relationship can be discussed based on the instructor/leaner relationship. Disaster education and risk communication is based on the assumption that if experts communicate the risk scenario and damage prediction to non-experts, non-experts will implement risk preparedness as mentioned as risk perception–proactive action framework. However, this one-directional education structure, in which experts teach non-experts, makes experts the active implementer and non-experts the passive followers. The passive attitude of non-experts is problematic because they often need to follow the expert's instructions to obtain knowledge and skills, but contradictory need to proactively apply them for risk preparedness. The following example of a tsunami evacuation drill in Zihuatanejo shows the problematic structure identified through the observations and interviews with Civil Protection officers, teachers, and police officers in Zihuatanejo.

A tsunami education campaign was organized by the municipal government in 2012 and the major schools, including Vicente Guerrero Primary School, participated in the campaign. Civil Protection officers, police, and the navy visited schools and gave lectures to students and teachers on how to evacuate in the event of an earthquake and tsunami. The experts designated and communicated the evacuation route to be taken from school buildings to the schoolyard and from the schoolyard to elevated land. They also created the evacuation drill schedule. Once the evacuation drill started, they guided students and teachers through the drill, from the school to the designated elevated place, blocking the traffic to ensure student safety. Thus, all the important knowledge and skills, such as the process of evacuation, the evacuation route, and how to ensure safety during evacuation, were actively shown by the experts to non-expert teachers, who were expected to follow the instructions. This style of evacuation drill is observed worldwide. However, in 2016, teachers in Vicente Guerrero Primary School commented that they knew the evacuation route given by the experts, but they were skeptical about whether the evacuation route was adequate because of the old bridge and heavy traffic along the route. The teachers did not discuss alternative evacuation routes because they believed that the disaster countermeasures given by the experts were correct. This demonstrated that the teachers remained as passive followers of the experts' instructions, and they took no action even though they were doubtful. It is also important to point out that this passivity engendered distrust in teachers towards experts because the teachers could not question the experts about alternative routes, even when they were skeptical of them. The fact that one-directional communication leads to distrust between experts and non-experts has also pointed out by the Feldman et al. [27] and Howard et al. [28]. Furthermore, the active expert/passive non-expert structure is problematic because the teachers who are the principal actors in evacuation cannot participate in the decision-making for the evacuation drill. The structure is also increased by the differences in levels of knowledge and skills. If the expert has more knowledge than the non-expert, the active attitude of the expert is increased with the behavior to teach the knowledge and skills, strengthening the passive attitude of the non-expert. This is known as the *deficit model* in science communication studies [32].

Importantly, the active knowledgeable expert/passive non-knowledgeable non-expert relationship and the catastrophic perception of tsunamis complement each other. As mentioned in the previous section, the catastrophic perception produces feelings of powerlessness and that taking measures is useless. Thus, tsunamis are not recognized as something that non-experts can deal with. This feeling generates a dependent attitude on expert knowledge and allows non-experts to follow the experts' knowledge and skills passively. From the experts' point of view, because non-experts rely more on the experts due to the catastrophic perception, experts teach non-experts knowledge and skills more actively. This positive feedback between the experts and non-experts is a deep-rooted problem that hampers tsunami education and drills in Zihuatanejo.

3.3. Knowledge of tsunamis

The ultimate goal of this study is to foster a proactive attitude among citizens in general and the teachers of Vicente Guerrero Primary School in particular, so that they can play an active role in tsunami-related education and promote voluntary evacuation behavior during real earthquakes and tsunamis. Accordingly, this section outlines the level of knowledge that citizens and teachers had about tsunamis in Zihuatanejo before the educational intervention conducted by the Civil Protection officers and the authors.

Previous studies on tsunami evacuation behaviors commonly indicated that the following factors induced proactive and voluntary evacuation: a general education level, including basic scientific knowledge;

socio-cultural aspects, such as past tsunami experiences; oral history and indigenous knowledge; community-based preparedness activities, such as evacuation drills; and circumstances such as the perceived intensity of an earthquake, earthquake damage, and existence of warning [33,34]. Here, the general education level, socio-cultural aspects, and community-based preparedness activities in Zihuatanejo are introduced.

Regarding the general education level of citizens over the age of 15 years in Zihuatanejo, 54.4% completed elementary school and 22.6% completed junior high school; 8.6% did not finish elementary school [21]. Hence, few received higher education. The authors reviewed the textbooks used in public elementary and junior high schools in Zihuatanejo, which are part of the official curriculum created by the Secretary of Public Education in Mexico and found that the terms "earthquake" and "plate tectonics" appeared in science textbooks for sixth-grade elementary school and second-year junior high school students. However, less than one page of each textbook was devoted to these concepts. There were no detailed explanations of the mechanisms and no illustrations. Thus, generally speaking, people in Zihuatanejo do not possess basic scientific knowledge about earthquakes and tsunamis. During the first educational intervention, the authors asked 17 teachers at Vicente Guerrero Primary School about the tsunami mechanism and tsunami risk in Zihuatanejo, but none of them could answer correctly (No.1 of Table 1). A lack of familiarity with the mechanisms of earthquakes and tsunamis among school teachers was quite common in other schools in Zihuatanejo [35].

This socio-cultural aspect is closely linked to the history of Zihuatanejo. According to the local historian and interviews with older residents conducted by the authors, a few families migrated to Zihuatanejo around 1900. They used to live on higher ground in Zihuatanejo and, according to the son of first migrant, they did not experience any hurricanes and tsunamis. Zihuatanejo has been a very small community for decades. However, the government began promoting tourism there in the 1970s, and soon thereafter many hotels and restaurants were built. Many impoverished people living in the mountains started migrating to Zihuatanejo to seek employment. As a result, the population increased from approximately 400 in 1940s to 125,000 in 2016 [21]. Therefore, most families living in Zihuatanejo are second- or third-generation residents. The residents of Zihuatanejo have a diverse historical and cultural background because they migrated from different parts of Mexico. This complicates the socio-cultural analysis because the perception of risk could be influenced by the fact that most residents used to live in the mountains culture and may thus unfamiliar with the hazards of coastal life. In fact, Acapulco, which is located in the same state as Zihuatanejo (i.e., Guerrero) has a community history of several generations living in the city. According to a study conducted by Nakano et al. [14]; the tsunami disaster educational activities held there did not lead to exaggerated fears, as was the case in Zihuatanejo. Because of the different historical background in Zihuatanejo, there was no oral history of tsunamis. In fact, the same questionnaire survey mentioned above asked "Are you aware of any tsunamis hitting Zihuatanejo in the past?" (In Spanish: ¿Usted tiene conocimiento sobre el tsunami que sucedió en Zihuatanejo en el pasado?); 35.7% of the parents (n = 284) and 40.4% of the students (n = 713) answered "Yes." Interviews conducted after the questionnaire survey found that those who answered "yes" knew about recent tsunamis but did not know about large-scale tsunamis in the past.

Community-based preparedness was also lacking in Zihuatanejo. Through interviews with government officials, teachers, and local journalists, the authors found that the only tsunami disaster education and community-based activities related to tsunamis held in Zihuatanejo was the previously mentioned educational campaign in 2012. Zihuatanejo city hall and some local schools conducting earthquake evacuation drills but reported that they were not aware of the risk of tsunamis. Section 4 introduces the evacuation movie clips we used to overcome these problems.

4. Four-way split-screen evacuation movie clips

4.1. Basic concept

Tsunami evacuation countermeasures can be explained by two approaches, according to Yamori and Sugiyama (2020, in press). One is the approach from human systems, such as evacuation drills. The other is the approach from natural systems, such as creating tsunami hazard maps and establishing early warning systems. Applying these two approaches independently causes the following problems. Typically, a school tsunami evacuation drill (human systems) follows the designated evacuation route and measures the time from the beginning to the end of the drill. Thus, the drill is assessed independently focusing on human systems without referring to natural systems, such as inundation simulations. However, even if tsunami hazard maps (natural systems) are widely available, they are not designed to support decision-making about evacuation strategies and the implementation of evacuation drills. Thus, integrated interfaces for the two isolated systems were proposed as a smartphone application by Ref. [36] and as a video by Sun [18]. [36] wrote that both interfaces show that "if people's physical movement (human systems) and the tsunami's physical behavior (natural systems) overlap in time and space even once, evacuation fails, while if they remain separate, evacuation succeeds." The studies demonstrated that an interface that displays an evacuation drill and tsunami inundation simulation simultaneously succeeded in changing the overly pessimistic attitude of people in Kuroshio, Japan. Furthermore, the interface ensured the participation of all stakeholders in the decision-making process for the evacuation strategy, thereby building trust among academia, local government, and residents, and implementing the tsunami evacuation drill. Thus, with the support of stakeholders, residents reach a mutual consensus on the idea that tsunami risk preparedness can affect the risk scenario and reduce damage in the event of an actual disaster. The four-way split-screen evacuation drill movie clips in this study applied the concept of the interface. The development process is described in 4.2.

4.2. Development of four-way split-screen evacuation drill movie clips

The development of the four-way split-screen evacuation drill movie clips was based on interdisciplinary collaboration between psychology (first and second authors) and tsunami engineering (third to sixth authors) to combine human systems and natural systems. In addition, the authors, Civil Protection officers, and school teachers collaborated to produce the tool. The development was targeted for Vicente Guerrero Primary School in Zihuatanejo. The development process is explained based on Table 1.

The first phase (Nos. 1–5 in Table 1) focused on communicating basic knowledge. To address the lack of knowledge among teachers mentioned above, the Civil Protection officers and the authors delivered lectures explaining how earthquakes and tsunamis occur off the coast of Zihuatanejo; the presentation included the use of graphics in a discussion of the history of tsunamis along the Guerrero (No. 1). Next, a workshop was held with 14 teachers, to design an evacuation route for the school (No. 4). In the first half of the workshop, the authors described the important points to consider when designing evacuation routes, including choosing the route with lowest risk of being blocked due to the collapse of structures after the earthquake, the route with the least traffic, the route farthest from the tsunami wave is most likely to hit first, and so on. In the second half of the workshop, the teachers were divided into groups to discuss potential evacuation routes based on these criteria given by the authors. Each group presented their ideas to the other teachers, the authors, and the Civil Protection officers, the various proposals were discussed, and finally a better evacuation route for Vicente Guerrero Primary School was agreed upon. The chosen route is relatively wide, has few tall or old buildings, little traffic, and quickly leads to higher ground. There were two significant improvements made to the tsunami evacuation strategy at this moment. One was based on the teachers' observation that the school was surrounded by a 2.5–3-m-high wall made of concrete blocks, which could collapse during an earthquake and pose a risk for the school children. Thus, it was decided that everyone should first assemble in the schoolyard and keep distance from the wall. The other improvement was the result of the consensus-making process. As mentioned earlier, when Vicente Guerrero Primary School participated in a tsunami evacuation drill in 2012, the teachers had doubted the safety of the designated evacuation route proposed by the experts. Throughout the workshop in the present study, the evacuation route was completely changed, and another evacuation route and evacuation site were agreed upon as safer among the teachers, the authors, and the Civil Protection officers. Thus, the teachers could proactively participate in the process of deciding the evacuation route and organizing and then conducting first evacuation drill since 2012 (No. 5).

Next, the process of developing the movie clip started. The following description corresponds to activities categorized as the second phase (Nos. 6–10 in Table 1). First, the human systems were visualized. For the tsunami evacuation drill held on March 25, 2017 (No. 6), two video cameras, a wireless microphone, and a global positioning system (GPS) recorder were used. One camera recorded the students' evacuation behavior from the start to the end of the drill in a zoomed-out video recording. The wireless microphone was attached to student A, a sixth-grade boy, to record his voice and the other video camera followed him along the trajectory of the evacuation drill in a close-up video recording. In addition, the trajectory was recorded by GPS. In this evacuation drill, students and teachers were able to gather at the schoolyard within approximately 2 min from each classroom and completed the evacuation to the designated site within 18 min.

The tsunami inundation simulation of natural systems was developed by the third to sixth authors. Prior to conducting the tsunami inundation simulation, a large number of earthquake slip distributions were synthesized using the random phase approximation method [37]. Only a brief description is presented in this study (for details, see Ref. [38]. The random phase approximation method allows for possible scenarios to be randomly generated using the slip source spectra obtained from SRCMOD, a database of historical earthquakes around the world [39], thereby taking into account the uncertainty inherent in the variability of the earthquake source. This method has been applied to many studies of subduction earthquakes (e.g., Tohoku, Japan by Ref. [40]; Nankai-Tonankai region, Japan by Ref. [41]. [38] confirmed that historical earthquakes in the Mexican subduction zone recorded in the SRCMOD database also have coherent slip spectra characteristics. In the present study, 200 possible earthquake slip distributions for this fault region were synthesized. The target magnitude was 8.4, which is based on the largest events in Mexico since 1700 [42,43].

Tsunami simulations were performed for all of the generated possible scenarios, and the one that caused the highest tsunami in Zihuatanejo Bay was considered the worst-case scenario. The governing equations of the tsunami simulation were based on nonlinear shallow-water equations [44]. The worst-case scenario was then simulated at a resolution of 5 m. Bathymetric and topographic raw data were obtained from the digitalization of Nautical Charts and LiDAR data, respectively. These were provided by the Department of Atmospheric Sciences of the National Autonomous University of Mexico. The domains cover the entire Zihuatanejo coast and the simulation results show that the first wave arrives in Zihuatanejo Bay approximately 12 min 30 s after the earthquake and that most of the lowlands and the urban center of Zihuatanejo is inundated. The estimated maximum tsunami run-up is 7.9 m. The preliminary results of the inundation simulation were presented to the teachers in activity Nos. 8 and 10 in Table 1.

The four-way split-screen evacuation drill movie clip merged individual video recordings and an inundation simulation into a single video (Fig. 3). The lower-right corner was a wide shot of the evacuation drill, showing all students evacuating; the upper-left corner was a close-up shot of student A; the lower-left corner displayed the comments made by student A during the evacuation drill; and the upper-right corner showed the tsunami inundation simulation with a red circle showing the school location, a pin showing the designated evacuation place, and a smiley face showing the location of the evacuees (students) according to GPS tracking data. In the center of the movie clip, a timer displayed the elapsed time since the evacuation drill started. Thus, the video conveys both the natural phenomenon and the human response simultaneously.

4.3. Results of visualization via movie clips

The interaction between the evacuation behavior (human systems) and inundation by the tsunami (natural systems) are vital in influencing the success or failure of the evacuation. To examine different interactions between the two systems, by assuming a delay in starting the evacuation, evacuation movie clips of the following three scenarios were prepared. In scenario 1, evacuation started when the earthquake shaking stopped, which allowed students and teachers to evacuate to the designated elevated land (Video 1). In this scenario, when the tsunami inundation starts at the shoreline, the students and teachers are at the middle of the slope outside of the inundation zone. It shows that the evacuation is successfully completed with time to spare. In scenario 2, evacuation was delayed by 6 min compared with scenario 1, and half of

Fig. 3. Four-way split-screen evacuation movie clips.

the students were caught by the tsunami (Video 2). Specifically, this scenario visualizes the students and teachers being caught just in front of the slope leading up to the designated evacuation site. Furthermore, this movie clip visualizes the tsunami coming from the direction of the evacuation site, rather than coming from behind the students as they evacuate. In scenario 3, evacuation was delayed by 11 min compared with scenario 1, and the tsunami arrives at the shoreline before the students even begin to evacuate (Video 3). In this scenario, the tsunami hits when the students and teachers are exiting the school gate. This demonstrates how the tall concrete walls surrounding the school can prevent those inside from seeing the approach of the tsunami, thereby delaying evacuation and leading to high casualties. Thus, scenario 1 shows a successful evacuation, whereas the other two scenarios show failed evacuations.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.ijdrr.2020.101803

Comments by Student A also help to shed light on how students think about evacuation drills. At the 45-s mark of Videos 1, 2, and 3, Student A says, "I wonder how long it will take for a tsunami to reach this place and if we're going fast enough to evacuate." At 2 min 5 s, Student A says "I think this height is safe from tsunami." These comments imply that the students are also proactively thinking about the evacuation and the interaction between the tsunami inundation and evacuation behavior. These inquiries by Student A were answered later.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.ijdrr.2020.101803

Video 1. Scenario 1 - Evacuation started soon after the earthquake shaking stopped.

Video 2. Scenario 2 - Evacuation was delayed by 6 min compared with scenario 1.

Video 3. Scenario 3 - Evacuation was delayed by 11 min compared with scenario 1.

Supplementary video related to this article can be found at doi: mmcdoino

Visualizations of simulated tsunami evacuations have been performed for risk communication in previous studies. Galaz et al. [45] developed a tsunami propagation simulator interface for tsunamis such as the 1995 Colima earthquake in Mexico, the 2017 Chiapas earthquake in Mexico, the 2001 earthquake in Peru, and the 2010 earthquake in Chile. The interface shows the epicenter, magnitude, tsunami propagation, tsunami height, and the time since the earthquake struck with the visual images. The interface was developed to facilitate science and risk communication to non-experts, thus it is accessible online and has also been exhibited for the public. Lonergan and Hedley [11] developed an augmented reality tsunami simulator, which allows the user to observe a 3D tsunami inundation simulation in an actual geographic space. These previous studies are effective risk communication tools; however, they did not consider the chronological interaction and interrelationship between the tsunami simulation and human systems, and did not use the simulation to conduct evacuation drills or improve evacuation strategies. The movie clip method is unique in that it visualizes the interaction, in real time, of the tsunami inundation (natural systems) and human behavior in an evacuation drill; it visualizes different potential scenarios resulting from inundation and human behavior; and it contributes to improvements in evacuation strategies, for example, by including student comments.

5. Application of the evacuation movie clip

The application of the movie clips corresponds to the third phase (Nos. 11 and 12 in Table 1). A workshop (No. 11) to reflect and provide feedback on scenarios 1–3 was held with 16 teachers from Vicente Guerrero Primary School, Civil Protection officers, and the first author on June 6, 2019. All the stakeholders watched the three clips, then the 16 teachers were divided into four groups and were asked to share their observations of the clips and to suggest evacuation strategies for the three different scenarios. The first author and the Civil Protection officer did not join the group discussion during this phase to avoid the influence of a knowledgeable active expert. After the discussion, each group presented the results of discussions (Table 3). Each group proposed evacuating to the designated evacuation place as the principal evacuation strategy. In addition, alternatives were also discussed, depending on the scenarios. Then, a general discussion among all the participants, including the Civil Protection officer and the first author, followed. All participants agreed with the following strategies. Teachers make their best effort to start the evacuation as quickly as possible towards the designated higher place considering scenario 1, and the teacher who guides the trajectory of the evacuation is responsible for measuring the time elapsed since the earthquake. If the teacher judges that there is insufficient time left to reach the designated area, they change to vertical evacuation in a nearby building, considering scenario 2. In scenario 3, teachers guide students to the second floor of the school building.

Table 3
Results of the discussion in each group.

	Scenario 1	Scenario 2	Scenario 3
Group 1	Conduct organized, quick, and secure evacuation to the designated elevated land.	Same as scenario 1, but the evacuation behavior is faster than in scenario 1.	Do not leave the school building. Climb to the roof and keep watch.
Group 2	Head to the designated elevated place.	Leave the school as quickly as possible towards the designated place. If the tsunami approaches, look for high buildings to climb.	Stay in the highest place in the school building and wait for rescue, hoping that the tsunami is small.
Group 3	Follow the designated evacuation route and pay attention to possible tsunami alerts.	Prepare plan B; in case of limited evacuation time, prepare two alternative routes with necessary height to be safe.	Climb to higher places in buildings or houses.
Group 4	Maintain calm and start the evacuation to the designated elevated place.	Teachers in charge of each class start individual class evacuation for quicker evacuation.	Climb to the roof top of the school and prepare stores for spending some time in school.

The general discussion during the workshop was also extended to the preparations for the next evacuation drill to test the effectiveness of the proposed strategies. Two ways of performing the evacuation drill were discussed for scenarios 2 and 3, which involved a vertical evacuation drill in a tall building along the evacuation route and a second-floor evacuation drill in the school building, respectively. To perform the evacuation drill, the teachers decided that one person should take charge of measuring the elapsed time, and they agreed to update the school Civil Protection committee and check the evacuation route inside and outside of the school. The evacuation drill to the second floor of the school was performed by the teachers on November 19, 2019 (No.12 in Table 1). Based on the discussion in the workshop, the teachers changed the gathering place for students to the schoolyard and had students line up for quick and safe evacuation. Furthermore, the school director did not inform teachers and students as to whether they should evacuate to the designated higher place or to the second floor of the school building prior to the evacuation drill. The judgement was made when all the students were moved to the schoolyard from each classroom and, assuming that a certain amount of time had passed, the director made the decision to evacuate to the second floor of the school building.

The initiatives of teachers inspired the Civil Protection officers to list the tall buildings in Zihuatanejo and confirm that they would be safe with the updated tsunami inundation simulation. The Civil Protection officers contacted two hotels on the list of tall buildings to request that they receive vertical evacuations in the case of a real tsunami emergency. One hotel agreed to be a government-certified official tsunami evacuation building and the other verbally agreed to receive the evacuation. The teachers of Vicente Guerrero Primary school are now planning a vertical evacuation drill using the tall building, based on a consideration of scenario 2. These facts demonstrate that tsunami preparedness is enhanced through the mutual actions of the Civil Protection officers and school teachers.

6. Effect of the application of evacuation movie clips

6.1. Improvement in evacuation strategies

Visualization of the interactions between human and natural systems had the practical effect of improving the tsunami evacuation strategies in Vicente Guerrero Primary School. The important outcomes were to foremost check the effectiveness of the evacuation drill. In particular, scenario 1 indicated that quick evacuation action would ensure that students and teachers had time to reach the designated evacuation place, whereas evacuation failed in scenarios 2 and 3, which permitted teachers to consider the alternatives. Thus, the tsunami evacuation strategy was revised. Before the intervention with the movie clip, the teachers had a single option to evacuate to the designated evacuation place. However, as natural systems were integrated into the discussion, agreement was reached on vertical evacuation to tall buildings and staying on the higher floor of the school building.

Following the revision in tsunami evacuation strategies, the drill itself was also revised. A new evacuation drill to the second floor of the school building was organized and implemented. Integrating the inundation of tsunami into the design of the evacuation drill, the teachers simulated the decision-making process of going up to the second floor of the school building measuring the time elapsed since the earthquake. Furthermore, they were positive in implementing the vertical evacuation drill considering Scenario 2. The Civil Protection officers agreed with these ideas, and administrative procedures were used to designate an evacuation building nearby Vicente Guerrero Primary School. Thus, the development and application of evacuation movie clips promoted the revision of evacuation strategies and evacuation drills based on consensus-making of risk scenario among stakeholders.

6.2. From catastrophic to realistic, from passive to active

One deep-rooted barrier hampering the active participation of teachers in tsunami risk preparedness was the catastrophic perception of tsunamis that induced feelings of powerlessness and the skepticism toward experts. Intervention using the tool that shows the interactions between the human systems and natural systems changed the perception of tsunamis from catastrophic to realistic. The tsunami inundation simulation gave a scientific basis for showing the tsunami height would not be as catastrophic as they thought and that the designated evacuation place would be high enough for tsunami evacuation. The movie clip showing scenario 1 also demonstrated the success of the tsunami evacuation. These facts helped the teachers propose second-floor evacuation if evacuation to the designated place could not be achieved. This decision shows that the teachers comprehended the complex interactions of evacuation and tsunami inundation in a realistic and scientific way. The teachers were allowed to propose different strategies considering that it was conceivable that the worst tsunami inundation scenario with low probability may reach beyond the height of the school building. In this case, the principal strategy is to evacuate to the designated place. However, this scenario is based on probabilistic modeling and there is a low likelihood that a tsunami of such height would occur. Taking into account the probabilistic hazard assessment and required time of evacuation from the school to the designated place, second-floor evacuation could be a better option if evacuation is delayed. The teachers participated in the complex decision-making process of deciding better evacuation plans depending on the scenarios. This clearly shows that teachers understood the tsunami inundation pattern, tsunami inundation velocity, arrival time, maximum inundation area, maximum tsunami height, and their effects on local evacuation behavior. Their catastrophic perception of tsunamis was modified to a realistic understanding, and through the process of consensus-making, they began to perceive tsunamis as something that non-experts can also deal with. It is also worth mentioning the changes in the teachers' level of knowledge before and after the educational intervention. As stated in Section 3.3, the teachers' knowledge about tsunamis was very limited, but as a result of the intervention, they developed the ability to design evacuation strategies by taking into account the uncertainty and probability of tsunamis.

The method of communicating risk through movie clips should also be discussed. In general, disaster education is based on the knowledgeable active expert/non-knowledgeable passive non-expert structure, which decreases the non-expert's involvement and participation. Use of the movie clips suggested the possible modification of the educational structure. The clips communicated updated scientific knowledge about tsunami inundation, and the knowledge was fully applied and used by the teachers in planning the evacuation strategy. This style of communication ensured the teachers' participation in the decision-making process and the planning of the evacuation drill, rather having them remain as passive followers of expert-provided knowledge. Consequently, they became less skeptical toward experts. In addition, this communication style led to the sustainable implementation of tsunami risk preparedness, such as evacuation drills at the school level, because the teachers developed more proactive attitudes. This shows the effectiveness of building consensus among experts and non-experts.

6.3. Accompanying effects of the movie clips

There were three additional positive effects of the development and use of the movie clips. One was related to local public insecurity. Zihuatanejo, Guerrero, which is exposed to various types of public insecurity caused by organized crime; 84.7% of the population in Guerrero feels insecure [46]. A Mexican national survey indicated that 71% of the respondents do not allow their children to go outdoors. The feeling of public insecurity is clearly reflected in the daily behavior of parents and teachers. Parents drop their children off and pick them up at the school gates every day. The school gates are open only during designated times in the morning and afternoon; at all other times, the school gate is locked with a padlock from inside and only a few teachers carry a key. The school grounds are surrounded by a 2.5–3-m-high concrete block wall to prevent intruders from entering the school. These measures ensure the students' security and parents' feeling of safety. These security measures make tsunami education and evacuation drills difficult to perform. Parents explicitly expressed their concern about taking the students away from the school premises during the tsunami evacuation drill at Vicente Guerrero Primary School, and some parents even followed their children during the drill. Because this insecurity makes it difficult for teachers to frequently conduct drills outside of the school. Therefore, by using the movie clips, they can still simulate different types of evacuation scenarios without having to worry about taking the students away from the school.

The second positive effect was the implementation of the consensus-making process in other schools in Zihuatanejo. The same program, from explaining the earthquake and tsunami mechanisms, to holding a workshop to design an evacuation route and conducting an evacuation drill, was implemented at two other schools. One primary school, because of the discussion among the teachers, the authors, and the Civil Protection officers, identified a shorter and safer evacuation route compared with the one they had already decided upon. In addition, the teachers implemented an evacuation drill based on their own initiatives and confirmed that they could evacuate to the newly designated evacuation site with time to spare before the estimated arrival of the tsunami. At the other school, the consensus-making process involved not only the teachers, but also student representatives. In addition to discussions with teachers about a better evacuation route, students participated in the process of identifying risks along the evacuation route, they created the tsunami evacuation map, and together with the teachers, experts, and Civil Protection officers, they agreed to conduct a tsunami evacuation drill based on the proposed evacuation route. Furthermore, the student representatives presented the proposed evacuation route and the accompanying risks at a morning assembly attended by 1200 students. These examples demonstrate that the consensus-making method of this study can be implemented at schools other than Vicente Guerrero Primary School. Based on these outcomes, a small booklet was developed and distributed to all 13 municipalities along the Pacific coast of Guerrero at the seminar given by the authors in November 2019. Thus, further verification of this methodology is required.

The third effect was the change in the perception of tsunamis from catastrophic to manageable in the schools, communities, and government of Zihuatanejo. The first author continues to carry out tsunami-related education, sharing updated scientific information with them, and their first responses were despairing. However, once they saw the movie clips and they understood that even the students at Vicente Guerrero Primary School can evacuate to elevated places, their perception of tsunamis was also modified. Thus, the movie clips can be used to not only consider evacuation strategies in Vicente Guerrero Primary School based on consensus-making among stakeholders, but also help change the perception of tsunamis in Zihuatanejo society.

7. Effective consensus-making with the use of scientific outcomes

This paper discussed not only the consensus-making process, but also how to communicate sophisticated uncertain and probabilistic scientific knowledge to the public. The key elements of applying scientific knowledge to society and multi-stakeholder participation can be ensured by the project design and the presence of a facilitator. The project "Hazard Assessment of Large Earthquakes and Tsunamis in the Mexican Pacific Coast for Disaster Mitigation" was designed comprehensively because it was performed by three groups. Group A investigated the seismic coupling at the plate interface based on seismic monitoring and geodetic observation data. The data from Group A was applied by Group B via construction of earthquake/tsunami scenarios based on earthquake/tsunami modeling. Group C developed an earthquake and tsunami mitigation education program to meet local needs, using the outcomes from Groups A and B. The project design functioned as a platform for implementing pure scientific earthquake monitoring, earthquake and tsunami modeling, and educational activities in the Guerrero coast area. Seismologists, engineers, and psychologists all focused on the same area in the project framework, which was important in realizing interdisciplinary collaborative research and producing updated scientific knowledge.

A social scientist was required to facilitate the scientific communication among three groups with citizens and government officers in the target area. The facilitator (the first author) worked with the local government and schools to identify local problems. In addition, the facilitator communicated with scientists in Groups A and B to identify scientific knowledge that could solve local problems. Thus, an educationalist or social psychologist with wide interdisciplinary knowledge is suitable as a facilitator. Comprehensive project design and a facilitator would improve the effectiveness of applying scientific data in the field to help science-based consensus decision-making with the full participation of the local stakeholders.

8. Conclusion

This study demonstrated that a catastrophic perception of tsunamis engenders a feeling in non-experts that tsunami risk preparedness is futile, and that the conventional educational structure engenders distrust of experts in non-experts experts and makes non-experts into passive followers of risk communicated by experts. Therefore, we developed four-way split-screen evacuation movie clips that display the interaction between human and natural systems, through interdisciplinary collaboration and multi-stakeholder participation. This tool effectively communicated the science-based tsunami risk scenario to non-experts and was effectively used in the discussion among researchers, Civil Protection officers, and teachers to build trust and reach a consensus on the risk scenario, thereby changing the perception of tsunamis from a catastrophe that non-experts cannot manage to a realistic perception that non-experts can indeed play a role in preparing for tsunamis. Furthermore, this change in perception promoted a proactive attitude among the teachers, which led them to revise the school's tsunami evacuation strategy, including drills. In other words, scientific knowledge about tsunami inundation was applied and localized by the teachers. A proactive attitude among teachers may be key to ensuring the sustainability of tsunami risk preparedness.

Considering the problems discussed in the paper, the perception of tsunamis as catastrophic events may be an issue unique to Zihuatanejo because Acapulco, which is also located in Guerrero, did not share this perception, according to Nakano et al. [14]. However, distrust of experts and the one-directional nature of risk communication are common issues around the world, as pointed out in Yamori [20]; Wachinger [12]; Feldeman et al. [27]; Brofman et al. [19]; and Howard et al. [28]. Thus, the methodology proposed in this paper can be applied to overcome the issues inherent in one-directional risk communication and build trust among stakeholders, which may lead to more proactive preparedness actions and voluntary evacuation response by local residents.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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