Applicability of Design Methodology for the Remediation Bund of Flammable Dangerous Liquid Storage Tanks

Ádám Berger 1, Lajos Kátai-Urbán 2,* , Zsolt Németh 1, Attila Zsitnyáni 2, and Zsolt Cimer 1

Abstract: The risk of flammable dangerous liquids stored on the industrial premises escaping into the environment in the event of major industrial accidents must be minimized. Such a risk reduction result can be achieved by the use of safety barriers, such as a remediation bund area, which can retain, collect and store the released material. The careful determination of design parameters of this installation is of great importance. Therefore, this study—based on the analyses of applicability of existing guidelines (SPCC and HSNOCOP 47)—will propose a new sizing calculation methodology to design optimal and efficient remediation bund parameters, including the remediation bund wall height and distance between the remediation bund and the storage tank walls. The design parameters are defined by applying Toricelli’s theorem and their practical compliance is tested using consequence analysis simulation software ALOHA 5.4.7 covering three possible major accident scenarios. As a result of the newly proposed methodology, the risk of overflow through the remediation bund wall can be excluded and higher effectiveness of the application of firefighting and technical rescue intervention activities can be ensured. The results of present research ultimately serve to prevent major industrial accidents and eliminate their possible harmful environmental impact.

Keywords: chemical storage; flammable dangerous liquid; sizing methodology; major industrial accident; remediation bund; storage tank

1. Introduction

This section contains background information and a literature review on fire safety aspects of chemical storage facilities including remediation bunds of storage tanks, analyses of the sizing requirements of remediation bunds for chemical storage tanks and the determination of the scope of the present research and related research objective.

1.1. Analyses of the Fire Safety Aspects of Chemical Storage Tanks and Their Remediation Bunds

Our daily lives would be unthinkable without the use of chemical products. The scale of chemical product utilization in industry or logistics is increasing on a yearly basis. In order to make these materials available for industry, chemical production and processing, storage facilities involving large quantities of flammable dangerous substances need to be installed and operated [1]. The same trend also applies to the chemical warehouses of the logistics sector due to the globalization of international trade relations [2,3].

Based on information from international accident databases [4–6], it can be concluded that a large number of major industrial accidents involving the release of dangerous substances are likely to occur at chemical storage facilities and warehouses.
Major industrial accidents among other things can have a catastrophic effect on the environment, people’s lives and health [7]. Thus, in order to effectively prevent their occurrence, many national scientific institutes and international organizations have carried out research on the identification and assessment of major industrial hazards [8–11]. In addition, the systematization of lessons learned from these events through national and international databases forms the basis for the adaption and revision of internationally applied legal regulation [12,13] and technical standards [14,15]. The operators of dangerous establishments are obliged to demonstrate the existence of the conditions for safe operation, preparing safety reports and emergency plans [16]. In addition, preventing the environmental impact of major industrial accidents is also an important task for legislators and operators of dangerous activities [17]. Operators of such an industrial site must carry out, amongst other activities, an environmental impact assessment prior to the construction process [18].

Based on the analysis of the chemical process safety literature [19–21], it can be established, that there is no ‘zero’ risk level for related technological processes. The reason is that the failure of technological equipment, the occurrence of external or internal incidents, domino effects and human factors cannot be excluded as an initial accident event. In this context, technical, human and organizational risk reduction measures, as well as proper maintenance practices, should be prioritized during design, construction, operation and maintenance activities related to among others chemical storage and warehousing installation like chemical storage tanks.

A number of risk assessment procedure and methodologies [22–25] are used worldwide, providing a comprehensive systematic risk assessment overview involving chemical storage tanks safety aspects.

Based on the main safety factors analyzed above, the dual role of risk assessment should be noted, namely:

- minimizing through preventive measures the likelihood of the release of flammable dangerous substances into the environment;
- minimizing harmful consequences and impacts during a major accident event by establishing appropriate safety barriers.

The chemical storage tanks contain, in most of cases, a large quantity of dangerous liquids; therefore, they are exposed to the risk of major fires, explosions and toxic spillages. In this case, the elements of risk management system should include the application of active and passive protection measures and the proper operation of an uncertainty management system [26]. In the case of dangerous liquids storage tanks, it is stipulated by various guidance documents [27,28] that they must be equipped with retention installation suitable for capturing of the released dangerous substance.

According to Walton, I.L.W. [29], the concept of the remediation bund is ‘a facility-including walls and a base-built around an area where potentially polluting materials are handled, processed or stored, to contain any unintended escape of material from that area until remedial action can be taken.’ Therefore, the remediation bund area is a space or facility designed to contain a dangerous liquid run-off in the event of a storage tank damage. For this practical reason, particular attention should be paid to the prevention of storage tank failure and especially the design of adequate remediation bund area.

1.2. Analyses of the Sizing Requirements of Remediation Bunds for Chemical Storage Tanks

The purpose of the remediation bund area is to retain, contain and store the dangerous liquid spillage in the event of a storage tank failure during a major industrial incident. In order to ensure that the remediation bund area can properly perform its function, several design considerations need to be taken into account. The design and operation requirements are addressed in a number of internationally accepted technical guidance materials dealing with industrial pollution preventions. Environmental effects of major industrial accidents depend to a significant extent on the amount of firewater used during the firefighting and technical rescue operations [30].
The United Nations Economic Commission for Europe published its methodological guideline titled ‘Safety Guidelines and Good Practices for the Management and Retention of Firefighting Water’ [31], where, among others, a number of internationally accepted firewater calculation practices are presented. The guidance document recommends the application of the following technical guidance documents and methodologies:

1. The ‘VdS 2557 Planning and Installation of Facilities for Retention of Extinguishing Water (VdS 2557) is a Guidelines for Loss Prevention issued by the German Insurers’ [32], which already takes into account the amount of contaminated firewater that may be generated when sizing the remediation bund area;

2. Compared to VdS 2557, the recommendations in the Swiss Firewater Retention Guidance document (Swiss Guideline) [33] are considered to present a simpler application procedure. According to the guideline, the theoretical volume of firewater depends on the following factors: fire safety concept; storage method; the fire hazard of stored substances, preparations and articles; size of the fire compartment area.

The above-mentioned guidelines are mainly applied for the dimensioning of firewater retention and storage installations to prevent a major industrial accident that may occur mainly in chemical warehouse facilities with large fire compartment areas.

Remediation bund installations belong to the pollution prevention system of hazardous substance storage tanks as independently installed facilities. The effectiveness of the remediation bund on one hand depends mainly on its resistance to external influences and the effectiveness of the bund material of the dangerous liquid spillages. On the other hand, the proper sizing of remediation bund area is an essential condition for safe operation of the storage tank installation.

In the case of dimensioning of remediation bund areas for dangerous substance storage tanks, the following guidelines, widespread in international operators practice, can be taken into account:

1. In accordance with the Health and Safety Executive (HSE) guidance criteria [34] the common industrial practice is to use a 110% and a 25% rate for the sizing of the remediation area. In the case of a single storage tank, the remediation bund volume shall be at least 110% of the volume of the stored material. In the case of a group of containers like chemical storage tank farms, the required remediation bund area’s capacity is 25% greater than the total volume of the containers stored, or 110% of the volume of the largest container [35];

2. The ‘United States Environmental Protection Agency (US EPA) Spill Prevention Control and Countermeasure (SPCC) Plan’ document [36] uses the 110% rule of thumb applied in the industrial practice and propose that the sizing methodology should take into account the rainfall in the territory concerned;

3. The ‘Environmental Protection Authority Secondary Bund System (HSNOCOP 47)’ guidance material [37], in its sizing recommendation, in addition to the requirement of installing appropriate remediation bund capacity, already takes into account the design for the elimination of the risk of overflow through the remediation bund wall.

A summary of results of the methodologies and recommendations briefly described above is illustrated in Table 1.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Title of Publication</th>
<th>Description of the Main Results of the Assessed Methodologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>VdS 2557</td>
<td>VdS 2557 Planning and Installation of Facilities for Retention of Extinguishing Water.</td>
<td>The required volume of the remediation bund takes into account the amount of contaminated fire water that may be generated. The input factors to be used for the calculations are the fire load factor, the fire area factor and the fire protection factor.</td>
</tr>
</tbody>
</table>
Table 1. Cont.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Title of Publication</th>
<th>Description of the Main Results of the Assessed Methodologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swiss Guideline</td>
<td>Swiss Firewater Retention Guidance document</td>
<td>The theoretical volume depends on the following factors: fire safety concept; storage method; the fire hazard of stored substances, preparations and articles; size of the fire compartment area.</td>
</tr>
<tr>
<td>HSE</td>
<td>Health and Safety Executive guidance criteria</td>
<td>60,000 m$^3$ is the maximum total capacity of the tanks in a remediation bund. Storage of incompatible materials in the same area is prohibited. The remediation bund shall be sized to 110% of the maximum tank capacity. Care shall be taken to ensure drainage of rainwater collecting in the remediation bund.</td>
</tr>
<tr>
<td>HSNOCOP 47</td>
<td>HSNOCOP 47—Environmental Protection Authority Secondary Bund System</td>
<td>In addition to determining the capacity of the remediation bund, it already takes into account the design for the liquid flowing out of the tank to break through the containment wall.</td>
</tr>
</tbody>
</table>

1.3. Determination of the Scope of the Research and Research Objectives

The commonly used calculation methodologies presented above are basically based on the determination of the required remediation volume. However, in order to fulfill the function of the remediation bund, it is advisable to consider additional technical requirements linked with consequences and impacts of major industrial accident events. In the various process safety literatures [38–40], there are number of publications on the identification of possible major accident scenarios and the modeling of the consequences and impact of these events on people, facilities and the environment. According to the study of Brambilla, S. and Manca, D., it can be found, that in the case of consequence analyses of major accident scenarios, the aim is to determine the extent or threshold levels of physical effects with geometrical parameters [41].

Therefore, the properly sized remediation bund areas are of great importance for the limitation of the major accident’s consequences in the event of a release of stored flammable dangerous substance. The remediation bund area is designed to contain the amount spilled liquid, one of the results of which is the ‘pool’ formed from the released dangerous substance. The size of pool surface primarily affects the size of the evaporation surface zone and also the development of the heat radiation, blast explosion or toxic hazard zones.

Another technical aspect is the question of the wall height of the remediation bund, which can have two important components:

- If the wall height is low, then it is easier to carry out firefighting and technical rescue operations, but due to the greater distance between the wall of the storage tank and the wall of the remediation bund, the installation space requirement within the plant is greater. Other important dangerous phenomena could be that the leaking dangerous substances’ liquid can flow over the remediation bund wall;
- At the same time, the high-walled remediation bund can provide a space-saving design, but can make it difficult to carry out firefighting and technical rescue operations. Furthermore, if the remediation bund area fills with liquid, the storage tank can float up, which can lead to a catastrophic storage tank rupture.

In the context of the above, the main aim of the present research is to develop a new sizing methodology for remediation bunds of flammable dangerous liquid storage tanks,
which taking into account—in addition to the existing calculation models based on the
determination of the required remediation volume—additional technical requirements
linked with consequences and impacts of major industrial accident events.

In the course of present research calculations, firstly the practical application of ex-
isting sizing methodologies (SPCC and HSNOCOP 47) introduced above, and then as a
comparison of the newly proposed methodology of the authors, will be presented.

The newly proposed calculation methodology will allow the determination of the
optimal and efficient design parameters for the remediation bund area to be constructed,
which contributes to increasing the safe operation of chemical storage facilities and to
increase the effectiveness of fire protection and technical rescue intervention activities.

The present research does not yet take into account the physical and chemical prop-
ties of the stored liquid dangerous substances, nor the shape, size and direction of the spill
out. However, the analysis of these parameters should be a part of further research work.

2. Materials and Methods

According to the research objectives defined in Section 1.3, the calculation results of
the existing (SPCC and HSNOCOP 47) and newly proposed sizing methodologies will be
compared. In the first step, input parameters for the application of sizing methodologies
will be presented. Afterwards, the testing of the applicability of sizing parameters with
consequence analysis simulation software will be performed. It is important to note, that
the assumptions and simplifications used in the calculation models correspond to the
design and operation factors used in the case majority of flammable chemical storage tanks,
so they result not only in theory, but also in the majority cases of practical findings to be
utilized in case of ‘real’ industrial objects.

2.1. Introduction of the Existing and the Newly Developed Sizing Methodology
2.1.1. Determination of Input Parameters for the Application of Sizing Methodologies

During the calculation procedures, a single-walled chemical storage tank is taken into
consideration, which is always located in the middle of the square shaped remediation
bund area.

Figure 1 illustrates the storage tank and remediation bund used for the calculation
procedures purposes. The height of the storage tank is marked with \( H \), while its radius is
marked with \( R \). The height of the wall bordering the remediation bund is marked with \( y \)
and its distance from the storage tank with \( x \). The size of these two latter parameters will
determine the volume of the remediation bund.

![Figure 1. Determination of the calculation parameters. Source: own research.](image-url)
An important point is that the same input parameters are used for the calculation procedures, which are listed in Table 2.

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Marking</th>
<th>Unit (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of storage tank</td>
<td>$H$</td>
<td>15</td>
</tr>
<tr>
<td>Radius of storage tank</td>
<td>$R$</td>
<td>7</td>
</tr>
<tr>
<td>Distance between wall and the storage tank</td>
<td>$x$</td>
<td>2</td>
</tr>
</tbody>
</table>

2.1.2. Application of US EPA SPCC Plan Sizing Calculation Methodology

In accordance with the US EPA SPCC Plan procedure, the remediation bund area must be sized to accommodate 110% of the capacity of the storage tank contain. The volume of the storage tank ($V_t$) and the remediation bund area volume ($V_f$) were calculated according to Formulas (1) and (2):

$$V_t = R^2 \times \pi \times H$$  \hspace{1cm} (1)  

$$V_f = [(R + x) \times 2]^2 \times y$$  \hspace{1cm} (2)

Using the parameters given in Table 2, for Formulas (1) and (2), the minimum remediation bund wall height ($y$) for which the above condition is met is 7.9 m, the volume of the storage tank is 2307.9 m$^3$, and the volume of the remediation bund is 2559.6 m$^3$. Accordingly, the capacity of the remediation bund determined in this way is greater than 110% of the volume of the storage tank inside, and it is considered to be appropriate.

2.1.3. Application of HSNOCOP 47 Sizing Calculation Methodology

The HSNOCOP 47 guidance material [37] in its sizing recommendation also takes into account the height of the remediation bund wall for liquid overflow ($Z$). In this case, Formulas (3) and (4), available in the guidance material, can be used to calculate the distance ($I$) between the remediation bund wall and the storage tank wall and the height ($Z$) of the remediation bund wall in case of liquid overflow.

$$I = \left[4(Z - h)(H - Z)\right]^{0.5}$$  \hspace{1cm} (3)

$$Z = 0.5H + 0.5h$$  \hspace{1cm} (4)

where:

$I$—distance between the remediation bund wall and the storage tank,
$Z$—height of remediation wall in case of liquid overflow,
$h$—height of the remediation wall,
$H$—height of the storage tank.

For the calculation with the HSNOCOP 47 methodology, using the parameters in Table 2 and $h = 2$ m, and applying Formulas (3) and (4), when the height of the remediation bund wall is 14.0 m. Using Formulas (1) and (5), the volume of the storage tank ($V_t$) is 2307.9 m$^3$ and the volume of the remediation bund ($V_f$) is 4536.0 m$^3$.

$$V_f = [(R + I) \times 2]^2 \times Z$$  \hspace{1cm} (5)

Based on the above results, the capacity of the remediation bund area determined is greater than 110% of the volume of the storage tank contains, and therefore it is considered to be appropriate.

2.1.4. Application of Newly Proposed Sizing Calculation Methodology

The newly proposed sizing methodology can be divided into two main calculation components.
With the help of the first component of the methodology, the remediation bund area can be designed for optimal \((x)\) and \((y)\) parameters. Optimal condition in this case means that the maximum outflow distance \((x_{T_{\text{max}}})\) of the retained liquid is determined in relation to the height of the storage tank \((H)\), and this is used to calculate the minimum remediation bund wall height \((y)\) and distance \((x)\) to ensure the required remediation bund area volume and to eliminate the risk of overflow through the remediation bund wall.

The value \((x_{T_{\text{max}}})\) is calculated using Toricelli’s theorem \([42]\), which defines that the outflow velocity \((v)\) can be calculated using Formula (6) \([43]\).

\[
v = \sqrt{2 \times g \times h'} \tag{6}
\]

where:
- \(g\)—the acceleration due to gravity \((\text{m/s}^2)\),
- \(h'\)—the distance between the surface of the liquid and the site of the hole \((\text{m})\).

The theorem outlines that there is a relationship between the height of the liquid and the velocity of the liquid leaving the storage tank through the hole. From the literature dealing with the application of the theorem \([44–46]\), it can be clearly identified that as the distance between the surface of the liquid and the hole increases, the velocity of the liquid flowing out also increases.

This description is invalid both for higher viscosities and in case of possible turbulences. For example, it is also not applicable for a description of the longer time flow jet in the case of small damage of a closed container, since the internal pressure will decrease in the absence of sufficient air supply. In this case, the model only provides a good estimation of the outflow in the first few moments after the container is damaged, when the internal pressure has not yet decreased significantly. Thereby, the model does not describe the subsequent lower pressure jet. However, the above fact and the rate and frequency of air replenishment depend to a considerable extent on the shape of the damage to the container and the viscosity or chemical behavior of the liquid; factors which cannot be taken into account in a general model.

Therefore, Formula (7) is derived from the formula of projectile motion \([46]\), which is

\[
d = \frac{v_0 \times \cos \alpha}{g} \times \left(v_0 \times \sin \alpha + \sqrt{(v_0 \times \sin \alpha)^2 + 2 \times g \times h} \right) \tag{7}
\]

where:
- \(d\)—horizontal distance of deflection \((\text{m})\),
- \(v_0\)—initial velocity \((\text{m/s})\),
- \(\alpha\)—angle subtended with the axis \((\text{x})\),
- \(g\)—the acceleration due to gravity \((\text{m/s}^2)\),
- \(h\)—the difference in level between the starting level and the axis \(x\) \((\text{m})\).

Since the direction of the outflow is perpendicular to the tank wall, the value of the angle \(\alpha\) is found to be \(0^\circ\). Thus, the \(\sin \alpha\) and \(\cos \alpha\) factors are eliminated from Formula (7).

In order to follow the derivation of the method, the relevant parts of the above formula have been unified with the previous notations in the article, resulting in Formula (8).

As the present study examines exclusively safety sizing issues, it was considered appropriate to apply the estimation given by Bernoulli’s formula for laminar flow and low viscosity, which provides an upper bound estimation level for the maximum distance of the outflowing liquid.

In this way, the outflow distance \((x_T)\) can be determined using Formula (8) as a function of the distance \((z')\) between the damage hole and the base of the storage tank.

\[
x_T = \frac{v}{g} \times \sqrt{2 \times g \times z'} \tag{8}
\]
When applying Formulas (6) and (8), it can be stated for all storage tank heights that the maximum value of \( x_T(x_{T\text{max}}) \) is equal to the height of the storage tank \( (H) \). However, it should be noted that this calculation method is only applicable for small holes according to the hydraulic theorem \( \frac{H}{h} \). [47].

Formulas (9)–(11) were developed by the authors for the purposes of this research by approximation and laboratory tests. For horizontal projectile motion, in case of a given \( (v_0) \) and \( (g) \), the distance of deflection depends on the angle \( \alpha \). The distance will be the maximum when the sine function in the horizontal projectile motion formula takes the maximum value (=1). This occurs when the angle \( \alpha \) is 45°. Therefore, for a given initial velocity and acceleration due to gravity, the distance of the deflection is greatest at an initial velocity of 45°.

The angles along the circumference of the triangle formed by joining the endpoints of the tank height \( (H) \) and the maximum outflow distance \( (x_{T\text{max}}) \) are 45°. Formulas (9) to (10) fit to this overall dimension, which can be ensured by the ratios \( \frac{1}{3} : \frac{2}{3} \) of \((x):(y)\) ratios. In the case of Formula (10), the multiplier of 1.05 is a safety factor based on the results of an experiment performed by the authors.

On the basis of Formulas (9) and (10), the height of the remediation bund area is 10.5 m and the distance between the storage tank wall and the remediation bund area wall is 5.0 m. The volume of the storage tank is 2307.9 m\(^3\) according to Formula (1) and the volume of the remediation bund area calculated using Formula (2) based on the first component of the method is 6048.0 m\(^3\).

\[
x = \frac{1}{3} \times x_{T\text{max}} \\
y = \frac{2}{3} \times x_{T\text{max}} \times 1.05
\]

As a result of the calculation, the capacity of the remediation bund area determined is greater than 110% of the volume of the storage tank contains, and therefore it is considered to be appropriate.

The second component of the methodology is used to calculate the minimum height of the remediation bund wall for a given distance \( (x) \) between the remediation bund wall and the storage tank wall.

Therefore, in this case, the engineering designer determines the value of \( (x) \), for which Formula (11) gives the required value of \( (y) \).

\[
y = 0.35 \times x_{T\text{max}} + 0.62 \times (x_{T\text{max}} - x) \]

Formula (11) is obtained by refining the \( \frac{1}{3} : \frac{2}{3} \) of \((x):(y)\) ratios used in Formulas (9) and (10). However, here \( (y) \) is determined for the given parameter \( (x) \), so it is necessary to input the value of \( (x) \) into Formula (11). This explains the \( "x_{T\text{max}}-x" \) term in Formula (11).

The procedure for this component is identical in all other elements and steps as described for the first component. The height of the remediation bund wall calculated using Formula (11) is 13.3 m.

The volume of the storage tank calculated using Formula (1) is 2307.8 m\(^3\) and the volume of the remediation bund area calculated using Formula (2) is 4312.4 m\(^3\). Accordingly, the capacity of the remediation bund area thus determined is greater than 110% of the volume of the storage tank inside it and therefore it is considered to be appropriate.

Further discussion on the meaning and applicability of the design equations presented in this subsection can be found in Section 3.4.

2.2. Test of the Applicability of Sizing Parameters with Consequence Analysis Software

2.2.1. Importance of the Application of Chemical Accident Consequence Analysis

In the Section 2.1, it was already stated that the size of the remediation bund area has an impact on the development of the hazard zones during a potential major accident
event. This effect can be studied via consequence analyses modeling, for which—in line with Section 1.1 of the article—several software simulation tools are available.

In real industrial circumstances, there are many influencing factors that cannot be fully simulated, or can only be approximated, or certain factors need to be neglected. However, the relevance of consequence analyses models and software—widely used around the world—is unquestionable in the field of chemical installation design. They have thus been substantially validated and verified through real industrial installation and operation practice including emergency response situations.

2.2.2. Tools and Parameters Used for Consequence Analysis of Present Study

The consequence analyses simulation software used for the purposes of this research is ALOHA (Areal Locations of Hazardous Atmospheres) 5.4.7, a widely used freely available software for modeling dangerous substance emissions and spread, heat radiation, blast wave and toxic effects. The software has been jointly developed by the US EPA Office of Emergency Management and the National Oceanic and Atmospheric Administration (NOAA) Emergency Response Division in 1988 [48].

It is reasonable for dealing with the introduction of the calculation parameters used for the consequence analysis calculations in the present study, which can be found in the following.

For the modeling purposes, a flammable dangerous substance in liquid form was firstly selected as the chemical material stored in the 2307.9 m$^3$ storage tank, so that the impact area can be analyzed in a complex way. Thus, the impact area will not only be the surface area of the pool, but also the area bounded by the heat radiation caused by the possible pool fire major accident reference scenario. The dangerous liquid chosen for the calculations is acetone, which is an organic solvent used and stored in very large quantities in chemical industry. This substance is colorless, has a sweet smell and is a liquid under normal environmental conditions. It has a melting point of about $-95 \, ^\circ C$, a boiling point of about $56 \, ^\circ C$ and a flash point of $-17 \, ^\circ C$. Acetone is highly flammable (H225) and can also cause severe eye irritation (H319) and drowsiness or dizziness (H336) [49].

After that, we can determine that meteorological data and surface roughness are considered indifferent for the purpose of the modeling; accordingly the simulation was run with a wind speed of 1.5 m/s, a Pasquali stability index of “F” and an average ambient temperature of 10 $^\circ C$.

The major accident event assumed in the simulation was the formation of a 0.7 m diameter circular damage on a 15 m high, 14 m diameter, fully filled storage tank at a height of 8 m from the bottom. It is stated that a volume of dangerous liquid corresponding to the volume of the storage area above the damage is released into the surrounding environment.

The selection of major accident scenarios for the purposes of simulation was also an important aspect in the modeling.

The following scenarios were simulated in the modeling:

• first scenario: the storage tank is in a remediation bund area of 256 m$^2$;
• second scenario: the storage tank is in a remediation bund area of 484 m$^2$;
• third scenario: the storage tank is in a remediation bund area of 1296 m$^2$.

Finally, it should be noted that the simulation program limits the size of the heat radiation zones for combustion for ‘pool fire’ reference scenario by the maximum diameter of the pool or, if there is a safety barrier like remediation bund, then by its area. Therefore, the wall height of the remediation bund area cannot be introduced into the model.

3. Results and Discussion

In this part of the paper, there are summaries of the results introduced in Section 2 and analyses of the parameters calculated by the different sizing calculation methodologies. Then, the discussion on the advantages and disadvantages of the application of each methodology is presented together with limitations issues of the applicability of the new methodology for real objects.
3.1. Results of the Application of Existing and the New Sizing Methodologies

The values calculated using the sizing methodologies described in Section 2.1 are summarized in Table 3. The parameters for the storage tank are given in Table 3, which gives a storage tank volume of 2307.9 m$^3$.

**Table 3.** Parameters calculated using different sizing methodologies. Source: the author’s own work.

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Input Parameters</th>
<th>Marking</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPCC</td>
<td>distance from storage tank</td>
<td>$x$</td>
<td>2.0 m</td>
</tr>
<tr>
<td></td>
<td>height of remediation bund wall</td>
<td>$y$</td>
<td>7.9 m</td>
</tr>
<tr>
<td></td>
<td>capacity of remediation bund area</td>
<td>$V_f$</td>
<td>2559.6 m$^3$</td>
</tr>
<tr>
<td>HSNOCOP 47</td>
<td>distance from storage tank</td>
<td>$x$</td>
<td>2.0 m</td>
</tr>
<tr>
<td></td>
<td>height of remediation bund wall</td>
<td>$y$</td>
<td>14.0 m</td>
</tr>
<tr>
<td></td>
<td>capacity of remediation bund area</td>
<td>$V_f$</td>
<td>4536.0 m$^3$</td>
</tr>
<tr>
<td>New Methodology</td>
<td>distance from storage tank</td>
<td>$x$</td>
<td>5.0 m</td>
</tr>
<tr>
<td>first component</td>
<td>height of remediation bund wall</td>
<td>$y$</td>
<td>10.5 m</td>
</tr>
<tr>
<td></td>
<td>capacity of remediation bund area</td>
<td>$V_f$</td>
<td>6648.0 m$^3$</td>
</tr>
<tr>
<td>New Methodology</td>
<td>distance from storage tank</td>
<td>$x$</td>
<td>2.0 m</td>
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<tr>
<td>second component</td>
<td>height of remediation bund wall</td>
<td>$y$</td>
<td>13.3 m</td>
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<tr>
<td></td>
<td>capacity of remediation bund area</td>
<td>$V_f$</td>
<td>4312.4 m$^3$</td>
</tr>
</tbody>
</table>

Figure 2 illustrates the storage tank based on the parameters in Tables 2 and 3, and the remediation bund walls for each calculation methodology. Brown color indicates the remediation bund walls defined according to the SPCC, green for HSNOCOP 47, pink for the first component of the new method and lemon for the second component of the new methodology. The liquid jet is marked in light blue color.

The results for the calculation methodologies showed in Table 3 and Figure 2 are examined in more detail as follows.

Firstly, the SPCC guideline scaled remediation area complies with the 110% rule, but still cannot fully perform its function. The reason for this is that, in the case of damage heights greater than ($y$), it may occur that the liquid flowing out of the storage tank falls over the wall of the remediation bund.
Beyond that, the remediation bund area sized according to HSNOCOP 47 meets both the 110% rule and the exclusion of the risk of overflow criteria. However, the \( (y) \) determined using this methodology is considered higher than would be practically necessary.

Finally, both components of the newly developed methodology are in compliance with both the 110% rule and the exclusion of the risk of overflow criteria.

### 3.2. Results of the Application of Consequence Analysis Software Simulations

The evolution of the thermal radiation zones for the first major accident scenario in the simulation described in Section 2.2 is illustrated in Figure 3. It can be clearly seen that for a remediation bund area of 256 m², the potentially lethal heat radiation occurs in a zone of approximately 25 m radius. And the radius of the zone associated with the heat radiation that is still damaging is approximately 58 m.

![Figure 3. First scenario: thermal radiation danger zone. Source: own research by ALOHA 5.4.7.](image)

The evolution of the thermal radiation zones associated with the second major accident scenario is illustrated in Figure 4. For the 484 m² remediation bund area, the potentially lethal heat radiation occurs in a zone with a radius of about 30 m. The radius of the zone associated with the heat radiation that is still damaging is about 78 m.

![Figure 4. Second scenario: thermal radiation danger zone. Source: own research by ALOHA 5.4.7.](image)

The evolution of the thermal radiation zones associated with the third major accident scenario is illustrated in Figure 5. For a remediation bund area of 1296 m², the potentially...
Figure 5. Third scenario: thermal radiation danger zone. Source: own research by ALOHA 5.4.7.

3.3. Discussion on the Application of Existing Sizing Guidelines and the New Methodology

Regarding the issue of effectiveness of existing and newly proposed calculation methodologies, the following main conclusions can be made.

The remediation area parameters calculated with help of each sizing methodology are introduced in Section 3.1. Based on the results of the methodologies presented in Table 3, it can be concluded that they enable the design of a remediation bund in accordance with the generally accepted and applied 110% rule.

Using the same \(x\) parameters, the SPCC procedure provided the smallest remediation bund wall height 7.9 m and volume 2559.6 m\(^3\); thus, this was the most appropriate remediation bund area for the storage tank capacity. In principle, this result is acceptable from an operator and regulatory point of view, as a smaller remediation bund area also means lower construction costs. In addition, the low wall height makes it easy to carry out any firefighting and technical rescue intervention operations. On the other hand, the disadvantage of this methodology is that it does not take into account the risk of the liquid spillage through the remediation bund wall in the event of a storage tank failure. In such a case, a ‘pool’ can form an unlimited surface area, which can generate environmental and industrial safety obstructions. These problems include, for example, leakage of a dangerous substance into the ground, human and structural injuries caused by thermal radiation, explosion blast wave and poisoning initiated by the vaporizing toxic substance.

Based on the HSNOCOP 47 guidelines, the designed remediation bund area has a wall height \(y\) of 14 m and a corresponding volume of 4536.0 m\(^3\). In case of a possible storage tank damage, the spilling out liquid would remain inside the remediation bund area, so it would form a ‘pool’ with a limited surface area. However, this method has the disadvantage that the wall height represents an additional construction cost and makes it difficult to perform firefighting and technical rescue intervention operations. It should be noted, however, that the limited ‘pool’ area may result in significantly smaller physical and health hazard zones compared to SPCC methodology, although these major accident impacts may persist for a longer period of time.

In case of the first component of the newly developed methodology, the remediation bund wall height \(y\) is 10.5 m. The distance \(x\) between the storage tank wall and the remediation bund wall is 5 m, and the corresponding volume is 6048.0 m\(^3\). This component of the methodology is aimed at determining the optimal remediation bund parameters; consequently, it gives a significantly lower \(y\) value compared to HSNOCOP 47 methodology. However, this reduction generates an increasing of the value of \(x\), which involves a larger area subtraction from the total area of the site. Also, the larger area requirement

lethal heat radiation occurs in a zone of approximately 58 m radius. The radius of the zone associated with the heat radiation that is still damaging is approximately 125 m.
has a negative impact on the safety distances set by the regulations. In this case, larger physical and health hazard zones are created compared to HSNOCOP 47 methodology, but durability of their impacts is lower. As a result, the operator of the site must consider whether the optimal remediation bund area parameters offer enough benefits to sufficiently offset the disadvantage caused by the larger area requirement.

In case of the second component of the newly developed methodology, the remediation bund wall height ($y$) of 13.3 m and a volume of the remediation bund is 4312.4 m$^3$. Thus, given the same ($x$) parameter, this component gives a higher ($y$) parameter than SPCC and lower than HSNOCOP 47 procedures. Anyway, the spilled-out liquid in the event of a storage tank damage still remains within the remediation bund area. In case of this component, the same pool area and durability of impacts as of HSNOCOP 47 methodology was obtained. From these results, it can be concluded, that the methodology should be acceptable from an operator and authority point of view. The results of the investigated procedure provide safer remediation bund parameters as determined on the basis of the SPCC procedure. The remediation bund designed according to HSNOCOP 47 is more cost-effective, because the wall height is 0.7 m lower, which results in lower construction costs. In addition, the possible firefighting and technical rescue intervention activities can be carried out somewhat more easily.

3.4. Discussion on the Limitation of the Application of the New Sizing Methodology and Their Formulas

In the following, the limitation issues of the application of sizing approaches and the practical applicability aspects of the formulas determined in Section 2.1.3 will be discussed.

The limitations of the application of newly developed sizing methodology are that they do not take into account the shape, the size and direction of the storage tank damage and the physical properties of the dangerous liquid contained. Accordingly, the characteristics of the storage tank and the physical properties of the stored liquid, like density, kinematic viscosity affects the fluid outflow velocity and distance. It follows that, for example, if a liquid with a higher kinematic viscosity is in the storage tank, the outflow velocity and distance of the liquid may be lower in the event of storage tank damage, and the opposite results also may occur in case of a lower kinematic viscosity. In such a case, it is therefore possible or necessary to reduce the wall height of the remediation bund area. For this reason, the inclusion of a correction factor into Formula (11) could be the subject of further research work.

In addition to the above limitation consideration, the aspects of the behavior of the outflowing liquids in the case of open and closed tanks are also an important theoretical question to be discussed. In particular, Toricelli’s equation is developed for an open tank, where the pressure on the liquid surface remains constant and is equal to the ambient pressure. In the case of closed tanks, the pressure on the liquid surface is not necessarily equal to the ambient pressure and it changes (decreases) during outflow.

When applying Toricelli’s equation for the purposes of this study—in addition to the explanations given earlier regarding the derivation of Formula (7)—the following practical considerations must be taken into account. In the case of the present study, given that for a liquid of average viscosity, the pressure drop is only temporary, since the interior of the tank is supplied with air through the damage in the form of a “bubble”, the liquid that flows out after the pressure has equalized and will travel approximately the same distance as it did initially. In addition, there was already underlined in the Section 2.1.3 that present study exclusively examines safety sizing issues, where laminar flow and low viscosity features are taking into account, which provides an upper tier estimation level for maximum distance of the outflowing liquid. Thus, it is not necessary to make additions for closed tanks at this stage of the research. Furthermore, it should be mentioned that an adequate estimation of the pressure drop is not possible due to the different elasticity of the container walls, the different density of the liquids and the turbulent behavior of the infiltrating air bubbles.
Based on the conservative principle of scaling for safety, which is widely used for the process safety design and sizing in chemical industry [50,51], it is sufficient for the developed formulas of Section 2.1.3 to take into account only the largest of the radius outflow when determining the relevant parameters (x) and (y) of the remediation bund. This is because, if the pressure in the tank decreases, the flow distance of the fluid flowing out through the breach will certainly be less than the maximum distance (xTmax) taken as the input parameter of the formulas of newly proposed sizing methodology. Therefore, the remediation bund determined using Formulas (9)–(11) is in line with the practice of sizing to 110% volume in industrial practice. Furthermore, the liquid flowing out through a breach in the container will certainly remain within the remediation bund.

3.5. Discussion on the Results of Consequence Analysis Software Simulation Calculations

Based on the consequence analyses software simulation procedure described in Section 2.2 and its results presented in Section 3.2, it can be concluded that the size of the remediation bund area has a significant influence on the development of the physical hazard zones. The results of the modeling are summarized in Table 4.

Table 4. The results of simulated event sequences. Source: own research.

<table>
<thead>
<tr>
<th>Major Accident Scenarios</th>
<th>Thermal Radiation Hazard Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;10.0 kW/m²</td>
</tr>
<tr>
<td>1. scenario</td>
<td>25</td>
</tr>
<tr>
<td>2. scenario</td>
<td>30</td>
</tr>
<tr>
<td>3. scenario</td>
<td>58</td>
</tr>
</tbody>
</table>

Table 4 shows that for all threshold values, the heat radiation zones of the third major accident scenario are twice as large as in the case of the first major accident scenario. Subsequently, the larger remediation bund areas result in more extensive thermal radiation zones, which necessitate an increase in safety distances.

In the case of the application of the ALOHA 5.4.7 consequence analyses simulation software, the engineering designer specifies whether the ‘pool’ created has a limited or unlimited surface area. It follows that it is the responsibility of the engineering designer to assess the risk of overflow through the remediation bund wall.

However, it should be noted that it is not possible to input the remediation bund wall height into the consequence assessment simulation model, so that the durability of the hazard zones and the boundary of the ‘pool’ cannot be clearly determined. Based on the second component of the newly developed methodology, the first event height of 13.93 m, the second event height of 12.07 m and the third event height of 7.73 m would provide the necessary remediation bund wall height, which can provide the required capacity against overflowing.

3.6. Discussion on the Applicability of the New Methodology for Real Objects

For both components of the new methodology developed by the authors, it is necessary to establish applicability constraints for real industrial objects.

First of all, the methodology applies to stationary cylindrical atmospheric liquid storage tanks. The base of the tank is in the plane of the surface. The potential role of the size of the tank, like the ratio of its height (H) to its radius (R), on the parameters of the remediation bund (x) and (y), has not yet been investigated by the authors in the present research.

Since the properties of the stored liquid have not been considered at this stage of the research, the authors used water at 20 ± 3 °C for the development of the methodology and for the purposes of laboratory tests. It is also important to note that further research is needed to develop the methodology applying also temperature, viscosity and density parameters.
In the presentation of the newly developed methodology, and thus in the calculations, the designed remediation bund has a square shape. Beyond that, the tank is located independently in the center of the remediation bund. The methodology does not take into account the exclusion of associated fittings and artefacts from the useful volume of the remediation bund. Thus, the possible volume constraints must be taken into account.

We need to investigate further the static design of the remediation bund and its resistance to mechanical stresses. It is primarily important that the safety designer ensures that the tank would be resistant to the forces like wave action caused by the fluid flowing out of the tank. This may require an increase of the parameter (x) determined on the basis of component ‘I’ of the newly developed methodology.

It can be concluded from the above that further improvements are still needed for the new methodology described in this publication. At the same time, the importance of the methodology lies mainly in the proposals for applying and improving the consequence analysis models and software, as well as in creating a research base related to their application.

4. Conclusions

Based on research results introduced and discussed in Section 3 of this study, the following final conclusions can be identified.

In the relevant technical literature, there are a number of remediation bund sizing methodologies, where the determination of the remediation bund size is typically based on the 110% rule. However, the majority of these methodologies do not take into account the risk of dangerous liquid overflow through the remediation bund wall during a potential major accident event. Consequently, during such an event, a properly sized remediation bund area cannot fully perform its safety design functions.

It can be stated that the first component of the newly developed methodology focuses on sizing the optimal remediation bund area. This component ensures the minimum wall height at which the remediation bund area size meets the 110% rule and also eliminates the risk of dangerous substance overflow through the remediation bund wall. The second component of the newly developed methodology gives the minimum remediation bund wall height for the distance between the tank wall and the remediation bund wall, in order to ensure compliance with the 110% rule and to exclude the possibility of overflow through the remediation bund wall. The height of the remediation bund wall can also significantly complicate the effectiveness of firefighting and technical rescue interventions.

A properly sized remediation bund area ensures that a ‘pool’ with a limited surface area is created in the event of a tank damage. The limited pool area results in smaller physical and health danger zones; thus, safety distances can be reduced subsequently. It is therefore proposed to complement the consequence analysis software with additional input parameters for the calculation performed on the basis of the second component of the newly developed methodology. The latter factor may be the subject of further research work.

Further research task should also consider that the newly developed remediation bund sizing methodology does not take it into account, among others, the physical and chemical properties of the stored dangerous substances in storage tanks, nor the shape, size and direction of the dangerous substance damage.

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