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Original Article

Structural stability analysis of waste packages containing low- and intermediate-level radioactive waste in a silo-type repository

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ABSTRACT

The structural stability of a waste package is essential for containing radioactive waste for the long term in a repository. A silo-type disposal facility would require more severe verification for the structural integrity, because of radioactive waste packages staked with several tens of meters and overburdens of crushed rocks and shotcretes. In this study, structural safety was analyzed for a silo-type repository, located approximately 100 m below sea level in Gyeongju, Korea. Finite element simulation was performed to investigate the influence of the loads from the backfilling materials and waste package stacks on the mechanical stress of the disposed of wastes and containers. It was identified that the current design of the waste package and the compressive strength criterion for the solidified waste would not be enough to maintain structural stability. Therefore, an enhanced criterion for the compressive strength of the solidified waste and several reinforced structural designs for the disposal concrete container were proposed to prevent failure of the waste package based on the results of parametric studies.

1. Introduction

Low- and intermediate-level radioactive wastes (LILWs) are inevitably generated in many countries operating nuclear facilities, and a radioactive waste repository is essential to dispose them of. Under the existing regulation, the repository authority requires wastes to be treated to satisfy the waste acceptance criteria (WAC) established to secure the safety of the repository. In the WAC, the structural integrity of the waste is one of the important concerns as it is anticipated that loads will be applied to the waste during the operation and post-closure periods [1]. The loads are induced by static pressure from the weight of the waste stack and backfilling materials or dynamic stresses during handling and transportation [1–6]. Therefore, operators of repositories worldwide have established their own site-specific stability criteria for solidified wastes loaded in a disposal container. These criteria are typically defined by the terms of the potential loads and the structural characteristics of the repository for a lifetime.

An LILW repository under operation or to be constructed can be categorized into three groups according to the depth: landfill, near-surface facility, and intermediate-depth repository [7,8]. Landfill and near-surface facilities, such as trenches or vaults, have been widely constructed and operated worldwide, and the mechanical load exerted on waste package during operation is not a concern as they are generally located near the ground surface (<30 m depth). Furthermore, the mechanical strength criteria for the waste in these types of repositories are relatively well established owing to the simplicity of the structure. In particular, the criteria in several countries require the minimum compressive strength of a solidified waste, that is, 3.44 MPa for cement-solidified waste and 0.41 MPa for bituminized waste [1,9,10] for the trench type facility in the U.S., 0.34 MPa for bituminized waste in France, and 7 MPa for cement waste in the U.K. [10–12].

However, a few of the silo-type repositories, classified as an intermediate-depth repository, have been constructed and operated only in Finland, Sweden, and Korea. In this type of facility, the waste package is generally located at approximately 100 m below the ground and typically stacked up in the silo. In the vertical "stacking-up" configuration, significant weight-loading induced by a combination of the self-weight of the waste package and that of environmental filling materials is expected. Thus, a more advanced level of structural integrity design should be considered for the waste package. Currently, only limited information on the design

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criteria is available. For instance, specific standards for the waste package in Finland and Sweden are not released to the public, whereas it is requested that solidified waste should have a compressive strength higher than 10 MPa in Switzerland where a repository does not yet exist [11].

The silo-type disposal facility operator in Korea has specified a compressive strength limit of 3.44 MPa for cementitious and polymerized waste. It should be noted that these standards were determined in accordance with the criteria for the trench facility in the U.S. [9,13]. This indicates that its WAC would be unsuitable for the waste package in the silo-type repository. Furthermore, the published database for silo-type repositories is not openly available to verify whether the existing criteria are conservative enough to secure safety. For the trench type repository, structural safety analysis in both accidents (e.g., aircraft collision) and normal operating conditions (e.g., corrosion of steel disposal containers) has been researched and published in a wide range. The published and accumulated safety analysis database has been utilized to design new trench type disposal facilities [2,14]. Therefore, more detailed structural integrity guidelines should be developed based on the safety analysis of a reference silo-type repository to provide a reference point to both newcomer countries and facility operating countries.

In this study, a static mechanical analysis was performed on disposal containers and loaded waste using the reference design of the silo-type LILW repository in Gyeongju, Korea. The design and dimensions of the waste package and disposal system were provided by the Korea Radioactive Waste Agency (KORAD). The disposal containers placed at the top and bottom of the silo were analyzed using COMSOL Multiphysics®. These two containers were selected because they represent two extreme cases: the container at the top has a lid, which undergoes significant bending stress caused by the backfilling materials, whereas the container at the bottom is exposed to the maximum static weight load at the bottom of the disposal stack. The stress states from the simulations were compared with the enhanced criteria for the mechanical strength of waste and container. In addition, the applicable mechanical strength criteria for waste are discussed based on the simulation results in terms of stresses to prevent failure of the disposal container. We also proposed a different design to enhance the structural stability of the waste package by reinforcing the support to sustain mechanical loads on the package system.

2. Methods

2.1. Specification of disposal facility and waste package

The specification of the disposal facility and waste package was provided by KORAD through official information disclosure requests. Multiple silos with the height of 50 m were placed 80 m below sea-level in the Gyeongju LILW repository, and the wall thickness of the silos was approximately 1–1.5 m. A total of 26 concrete disposal containers containing radioactive waste drums were stacked vertically inside the silo, as shown in Fig. 1. After placing all the containers, the space between the top container and the dome of the silo was filled with backfilling material, which is a mixture of crushed granite and shotcrete.

In this study, only the 16-pack disposal container was considered and the 16-pack disposal container containing 16 waste drums has reference dimensions of 2.73 m × 2.73 m × 1.14 m, while the volume of each drum is 200 L. All the components of the container are made of general concrete, except the lid, which is made of reinforced concrete. There are four supporting columns at the corner of the container with the shape of a triangular prism with dimensions of 7 cm × 7 cm × 89 cm. The height of the supporting column is 6 mm higher than that of the 200-L drum to ensure that a 6 mm gap exists between the lid and drum.

The weight of the empty 16-pack disposal container and the lid is approximately 7000 kg, and, to investigate the structural stability with a conservative approach in the regulatory aspect, the maximum weight limit, 1000 kg was applied to the weight of the 200-L drum. In addition, to reflect a realistic scenario, the 200-L drum with half of the maximum weight limit, 500 kg was also analyzed. The weight exerted by the backfilling materials applying downward forces to the container was calculated assuming that the mixture ratio of crushed granite and shotcrete was 9:1. The densities of the crushed granite and shotcrete at room temperature are 1650 kg/m^3 and 2327 kg/m^3, respectively [15,16]. The weight load, without considering constraint force by shotcrete, on the lid of the disposal package at the top of the stack exerted by the backfilling material, σ, is obtained, as expressed in the following equation:

$$\sigma = \rho \times g \times z \tag{1}$$

where ρ is the density in kg/m^3, g is the gravity acceleration constant, and z is the height of the backfilling material in m.

2.2. Finite element modeling

2.2.1. Model geometry

The waste package at two selected positions was used in the modeling, as previously mentioned. The lid of the container is composed of reinforced concrete with embedded structural steel. The geometry of the lid was designed to support the weight of the container.

The container at the bottom of the package stack is expected to be exposed to the highest stress, compared with other containers, owing to the summation of the weight of the stacked containers and backfilling material. Moreover, the geometry of the 200-L drum and its complicated details, including grips and baring pads, were excluded in the model to obtain a conservative situation in which drums cannot function as structural support and to improve calculation convergence.

Three containers piled vertically were designed in the model used to verify the structural stability of the bottom container in the silo, as shown in Fig. 2(a). The model represents one column of the stacked containers in the silo, where the middle container of the model was set to have the weight of 24 waste packages in the middle. The weight of the 24 waste packages was additionally applied to the lateral wall of the middle disposal container in the model as the load exerted by the weight of the upper containers is mainly transferred through the wall, as shown in Fig. 2(a). The loading condition in the model was set by changing the weight of the waste in the top container as 500 kg and 1000 kg, which are for the normal and worst case, respectively. In addition, as the lid of the bottom container is expected to be less than the space between lid and solidified waste, the non-contact condition between the lid and waste is expected. Thus, the bottom container in the model was assumed to be an empty waste package as non-existence of the waste inside the container would not affect the result.

2.2.2. Boundary conditions

Weight load was imposed as the boundary condition at the top surface of the container in contact with the backfilling medium. The pinned boundary condition was imposed at the bottom surface of the bottom container as the bottom surface is constrained by the repository environment, as shown in Fig. 2(b). In addition, no constraints were applied to the lateral wall of the container considering the small space between the waste package and the wall of the silo. Among several contact conditions available in the

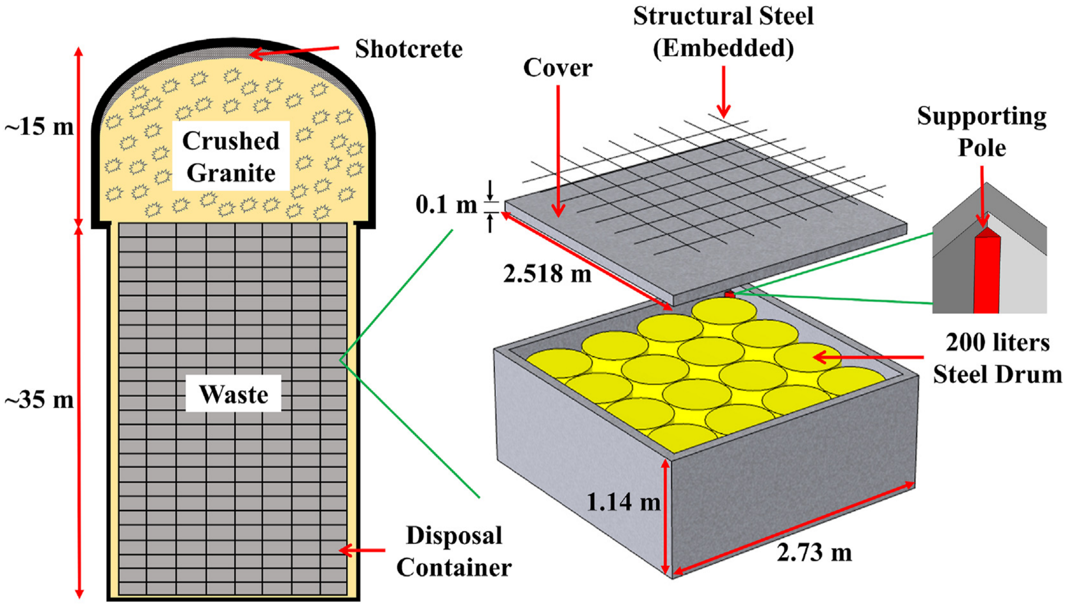


Fig. 1. Schematic of the silo-type LILW disposal facility in Gyeongju, Korea, and geometry of the 16-pack container.

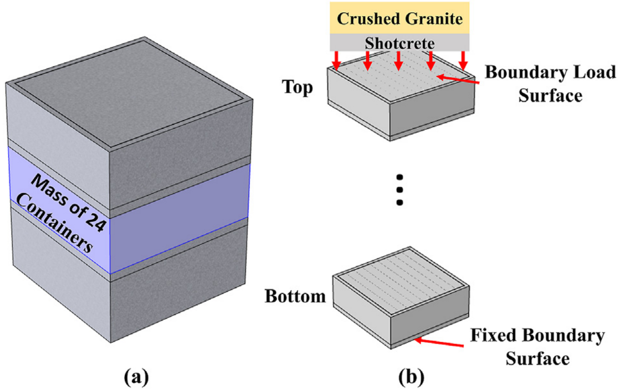


Fig. 2. (a) Additional mass condition to reflect the weight of 24 containers between the top and bottom containers and (b) boundary conditions for all the models.

modeling, the penalty method was applied for contact analysis, which allows limited penetration between contact surfaces. Contact conditions were applied between the lid and supporting poles, between the container top surface and container bottom surface, and between wastes and the bottom surface of the container. The surface of the lid and the bottom surface of the container, which are expected to be more deformed than the opposite surfaces of each contact pairs, were set as the destination boundary, and the opposite surfaces were set as the source boundary. In the modeling of the reinforced container, additional supporting poles were added in the contact condition to reflect the additional poles that were cured separately.

2.2.3. Test matrix

All the models used in the simulation and their objectives are summarized in Table 1. Model #1 verifies the structural stability of the bottom container under pressure exerted by the weight of the backfilling material and upper containers without constraint force from the shotcrete, as shown in Fig. 2(a). Model #2 verifies the pressure which causes the structural instability of the top container under the existence of constraint force. Model #3 verifies the structural stability of solidified waste under direct stress owing to the broken lid of the top container by varying the values of Young's modulus and compressive strength. Model #4 examines the effect of reinforcement of containers using three different designs, as shown in Fig. 3. In particular, solidified waste was excluded in Model #2 to reduce the calculation time owing to its modeling objective, as presented in Table 1. In Model #4, different designs of the reinforced container were modeled by changing the number of the additional reinforced supporting poles installed in the waste package. Furthermore, Model #4 was constructed by changing the number of stacked reinforced waste package at the top position where the waste packages are directly pressurized by the backfilling material. The empty container is placed at the bottom of the model to reflect bending of the reinforced container floor, as shown in Fig. 4.

2.2.4. Mesh design

All the meshes have tetrahedral shape, and the mesh of the destination boundary under the contact condition was set denser than that of the source boundary to ensure faster convergence, as shown in Fig. 5. The mesh density of the model parts where the deformation gradient is insignificant was set to coarse through partitioning to reduce the calculation time. The mesh was constructed to satisfy a minimum element quality larger than 0.1, which is the recommended value in COMSOL.

2.3. Material properties of container and waste

2.3.1. Original Drucker–Prager criterion

The Drucker–Prager (DP) yield criterion, which is widely used for pressure-dependent materials, was applied to calculate the plastic deformation of the concrete. The DP yield criterion uses the following function:

$$\sqrt{J_2} = A + BI_1 \tag{2}$$

where I_1 is the first invariant of the stress tensor and J_2 is the second invariants of the deviatoric stress tensor. The stress invariants are defined as follows:

Table 1
Test matrix of the models.

Model #	Description
1	To verify the structural stability of the bottom disposal container under the weight of the backfilling material and containers above.
2	To determine the pressure that causes structural instability of the top disposal container, which is directly pressurized by the backfilling material.
3	To determine the minimum compressive strength of solidified waste at the top position when the lid is broken by varying Young's modulus (5, 10, and 25 GPa) and compressive strength (4, 8, and 10 MPa).
4	To verify the structural stability of the reinforced container at the top position and an empty container at the bottom by implementing center, uniform, and full reinforced designs with one, two, and three reinforced stacks.

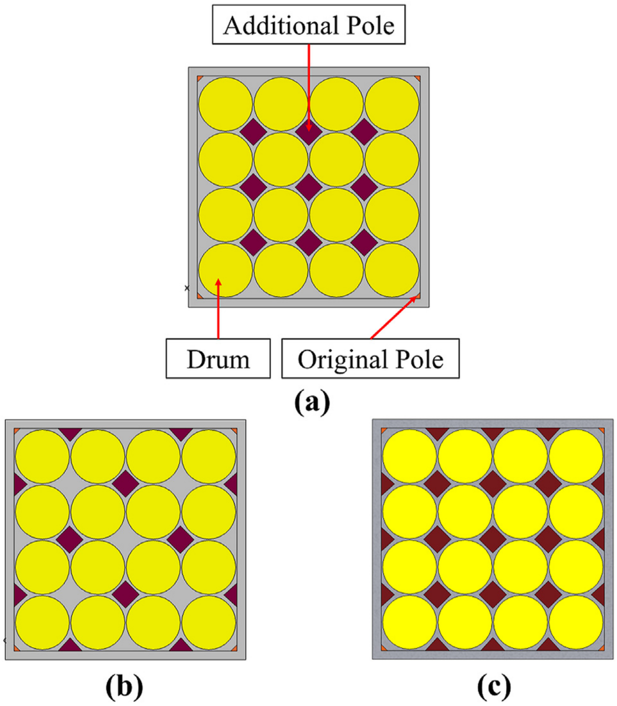


Fig. 3. (a) Center-reinforced design, (b) uniform-reinforced design, and (c) full-reinforced design.

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \quad (3)$$

$$J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \quad (4)$$

where σ_1, σ_2, and σ_3 are the first, second, and third principal stresses, respectively.

The terms *A* and *B* in Eq. (2) are the constants of the material determined via experiments, including uniaxial, biaxial, and triaxial compression tests. These constants are often expressed in terms of cohesion (c) and angle of internal friction (φ), which are used to express the Mohr–Coulomb yield surface, as the DP yield surface is a smooth form of the Mohr–Coulomb yield surface [17]. The constants were obtained by matching the DP yield surface with the external intersections of the Mohr–Coulomb yield surface, and they are expressed as follows:

$$A = \frac{6\ c\ \cos\varphi}{\sqrt{3}(3 - \sin\varphi)},\ B = \frac{2\ \sin\varphi}{\sqrt{3}(3 - \sin\varphi)} \quad (5)$$

As shown in Fig. 6, the elastic behavior of the model is expected when the data points (nodes on the geometry) are in the region below the yield criterion, whereas the plastic behavior of the model is expected when the data points are on the yield criterion.

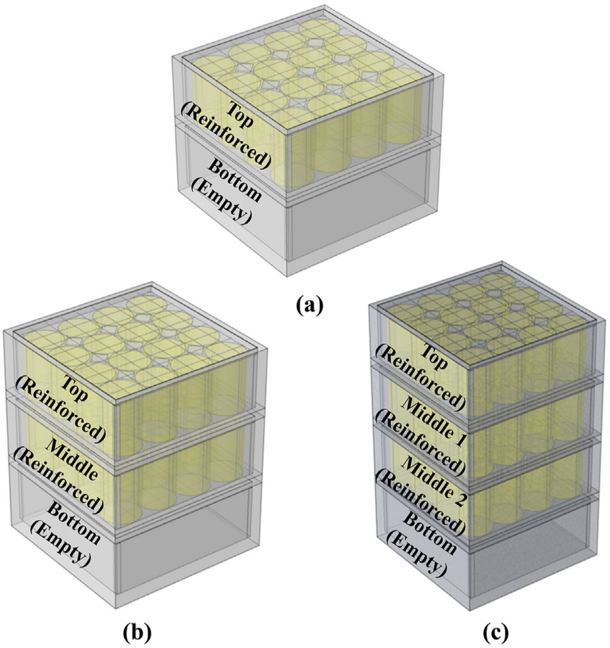


Fig. 4. (a) One, (b) two, and (c) three stacked reinforced containers implemented in Model #4.

2.3.2. Material property

The material properties applied in the modeling are listed in Table 2. The compressive strength of concrete containers was assumed to be 35 MPa that is close to its actual strength, and three different compressive strengths were assumed for the solidified waste: 4 MPa that is close to the compressive strength criteria, 8 MPa for the case where 4 MPa strength shows plastic behavior, and 10 MPa which is criteria in Switzerland. Three different Young's moduli (5, 10, and 25 GPa) were applied to each compressive strength of the solidified waste since solidified waste with a low compressive strength is likely to have lower Young's modulus compared with general concrete [18]. These three values of compressive strength and Young's modulus were used in the parametric studies. The Drucker–Prager parameters for each compressive strength were obtained from the Mohr–Coulomb experimental parameters [19]. It should be noted that the parameters of solidified waste for the constants in the DP yield behaviors in the low compressive strength region were obtained by extrapolation, as shown in Fig. 7.

3. Results

3.1. Structural stability analysis of the bottom container (model #1)

The third principal stress in the result was compared with the uniaxial compressive strength as it represents the largest

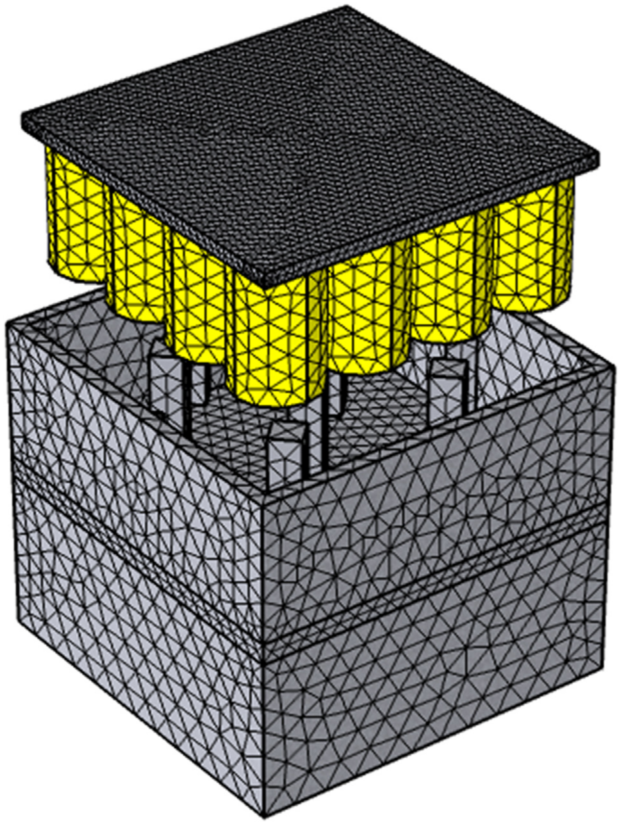


Fig. 5. Geometry with tetrahedral mesh obtained by varying the mesh size.

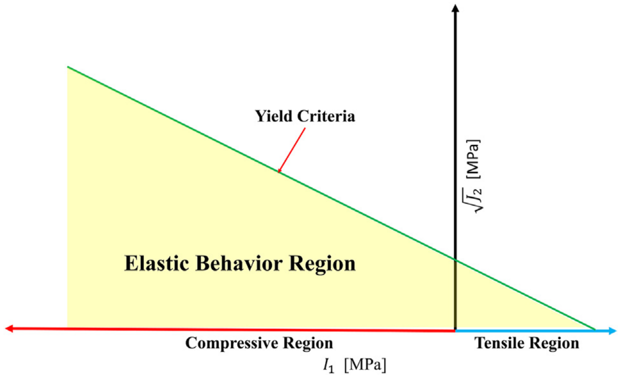


Fig. 6. Drucker–Prager (DP) yield criterion in 2-D. The region on the red line is the compression-dominant region, whereas that on the blue line is the tension-dominant region. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

compressive stress (i.e., the most negative stress). As shown in Fig. 8(a) and Fig. 8(c), when the weight of the solidified waste was assumed to be 500 kg which is for the normal operation case, the

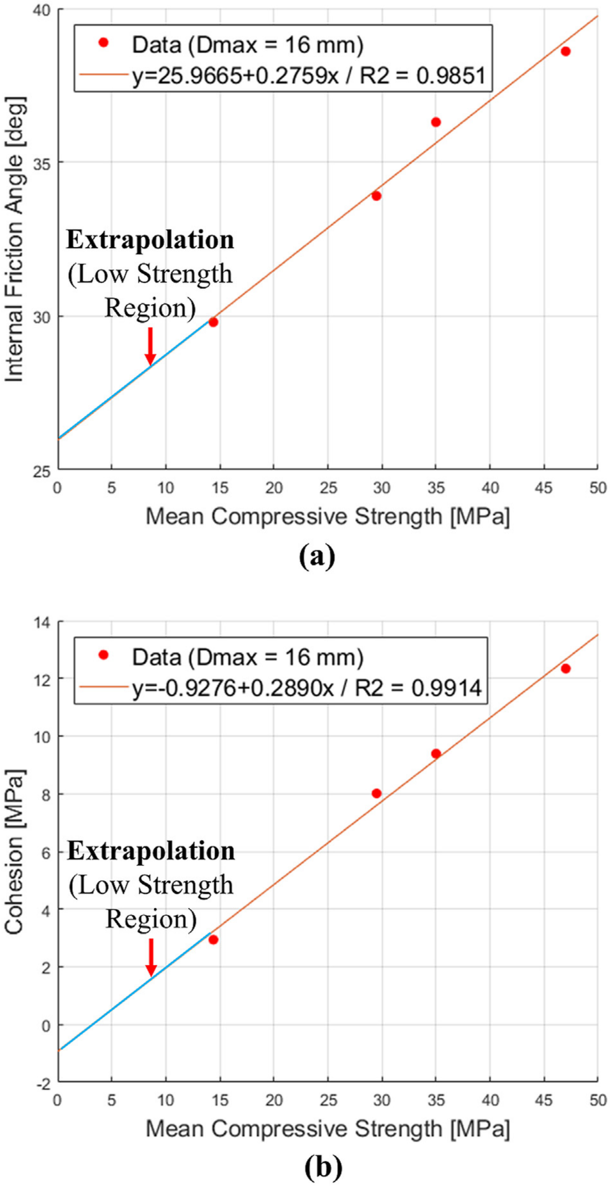


Fig. 7. Linear regression of (a) internal friction angle versus mean compressive strength and (b) cohesion versus mean compressive strength.

maximum compressive principal stress is 8.9 MPa, which is smaller than the compressive strength of the container (35 MPa). The strain due to the maximum compression is 0.03%, which minimally affects stability. The DP yield graph also exhibited only elastic behavior, as shown in Fig. 8(e).

When the weight of the solidified waste was assumed to be 1000 kg, which is the maximum weight, the maximum uniaxial compression is 11.9 MPa, and the maximum uniaxial strain is 0.04%. The DP graph exhibited elastic behavior, as shown in Fig. 8(b), (d),

Table 2
Material properties of the disposal container and waste.

Component	Material	Density [kg/m^3]	Young's Modulus [GPa]	Compressive Strength [MPa]
Disposal Container	**Concrete**	2300	25	35
Solidified Waste			5, 10, 25	4 8 10

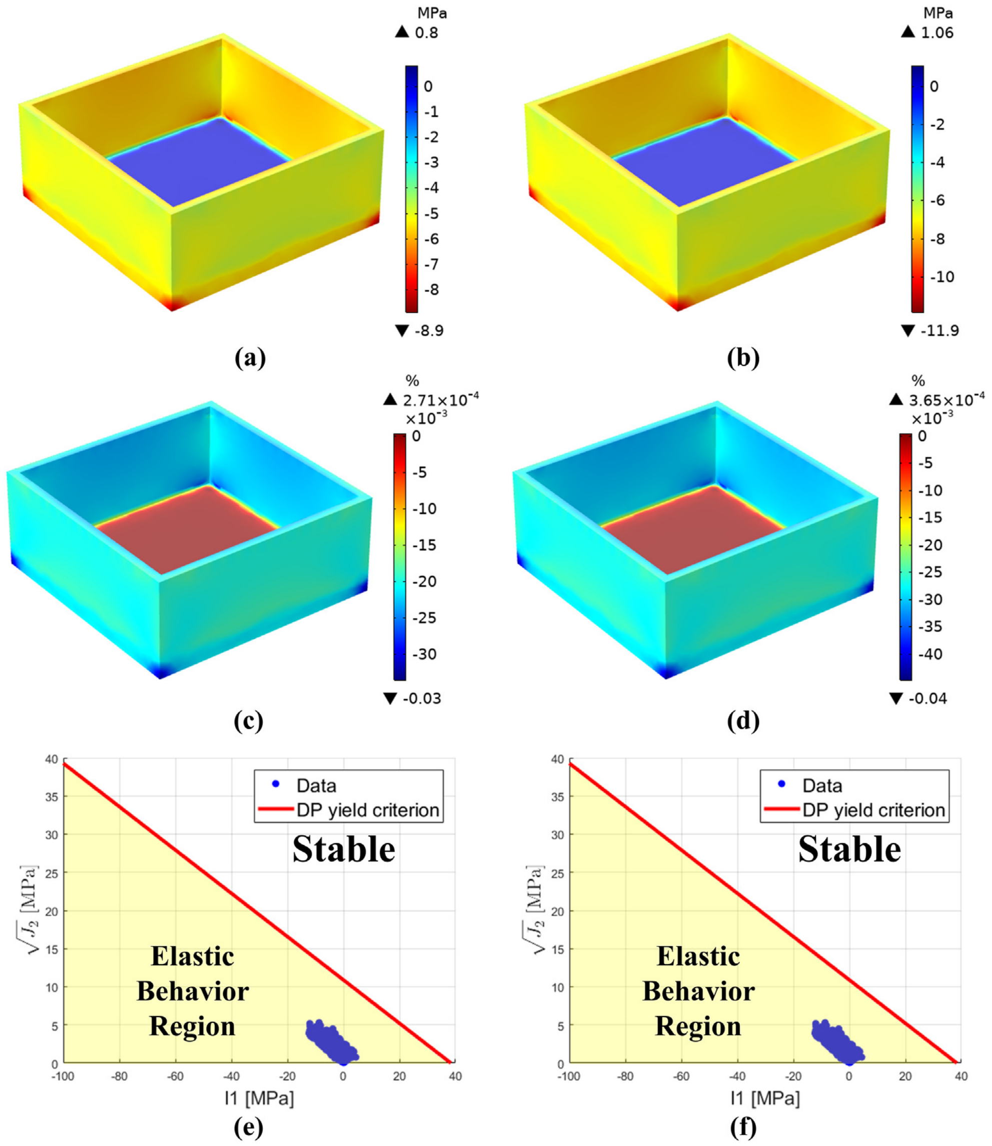


Fig. 8. Maximum uniaxial compression, strain results, and DP plotting of 16-container with (a), (c), (e) 500 kg and (b), (d), (f) 1000 kg waste.

and Fig. 8(f). This indicates that the stability of the container at the bottom of the stack is guaranteed under the given weight loading.

3.2. Expected loading showing the instability of the top container (model #2)

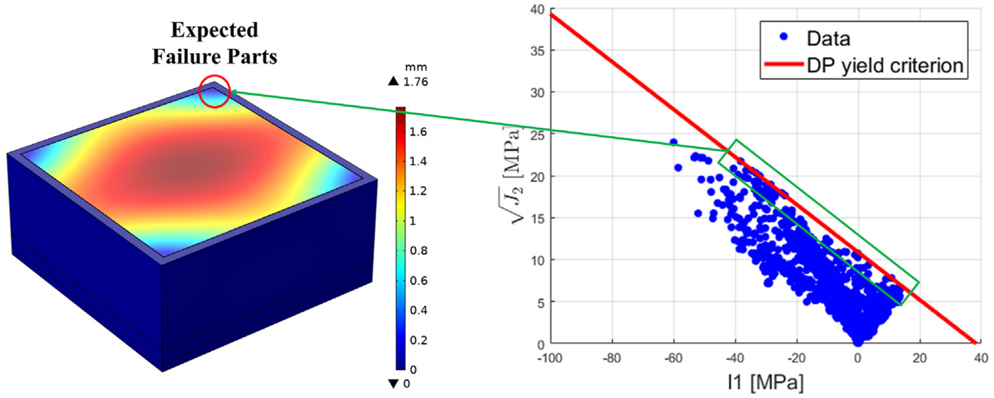
In Model #2, static weight loading was applied on the lid of the container at the top of the package stacking. It should be noted that the loading was gradually increased up to the maximum loading during the simulation to avoid severe contact penetration between the lid and support poles at every corner of the container.

The top container exhibited instability at only ~6% of the expected weight loading. The maximum displacement was 1.76 mm, which is much smaller than the space between the waste drums and lid (6 mm), as shown in Fig. 9(a). The DP graph indicates that the finite elements that yielded are located at the interface between the lid and supporting poles; this is determined by tracing back the points, as shown in Fig. 9(b). Therefore, the existing package design cannot guarantee the structural support of the waste drums and container specifically positioned at the top of the vertical stack when the expected weight loading is fully exerted.

3.3. Enhancing the compressive strength of waste under direct pressure (model #3)

In Model #3, various uniaxial compressive strengths (UCSs) of waste were parametrically selected to find the enough compressive strength of the solidified waste to endure the direct stress. For a more conservative approach, it was assumed that the disposal container has already failed, and the solidified waste drums were exposed to the full expected loading.

The waste experienced direct pressure without the lid, as shown in Fig. 10. The waste with a compressive strength of 4 MPa yielded regardless of the value of Young's modulus. The waste with a compressive strength of 8 MPa exhibited elastic behavior, except when Young's modulus is 25 GPa. The waste with a compressive strength of 10 MPa did not exhibit plastic behaviors regardless of the value of Young's modulus. In addition, the stress was mainly



(a) (b)

Fig. 9. (a) Maximum displacement of the top container and (b) DP plotting below ~6% of the expected pressure.

concentrated at the edge of the waste regardless of the value of Young's modulus, as shown in Fig. 11.

3.4. Reinforced container stability (model #4)

In Model #4, the top container, which exhibited instability in contrast to the container at the bottom of the stack, was reinforced to withstand the expected weight loading without plastic deformation. DP graphs of containers at different positions were plotted separately, as shown in Fig. 12. The center-reinforced container exhibited plastic behavior regardless of the number of reinforced stacks. In addition, with center-reinforced container, the empty bottom container exhibited the plastic behavior when only one stack is reinforced. In the uniformly reinforced container, one stack

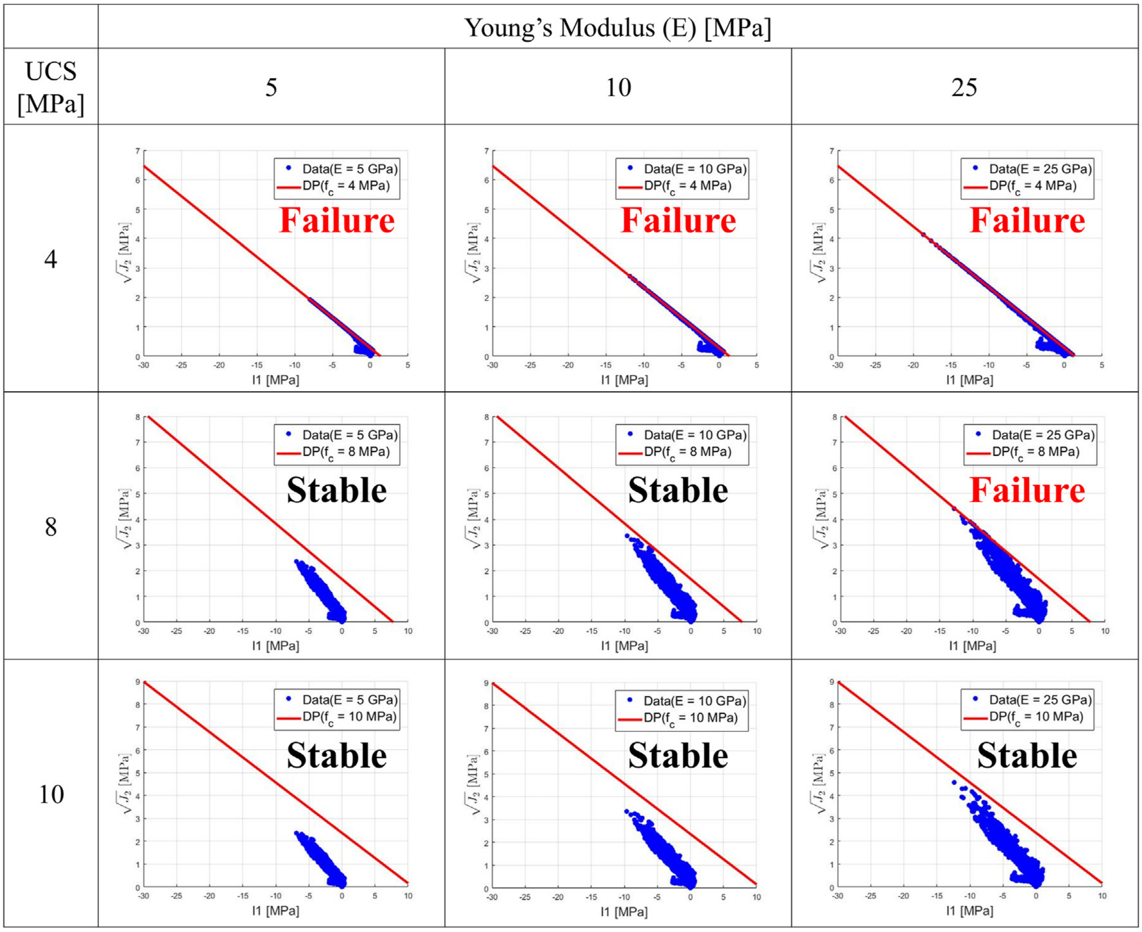


Fig. 10. DP plotting for different values of compressive strength of waste (4, 8, and 10 MPa) obtained by applying different Young's moduli (5, 10, and 25 GPa).

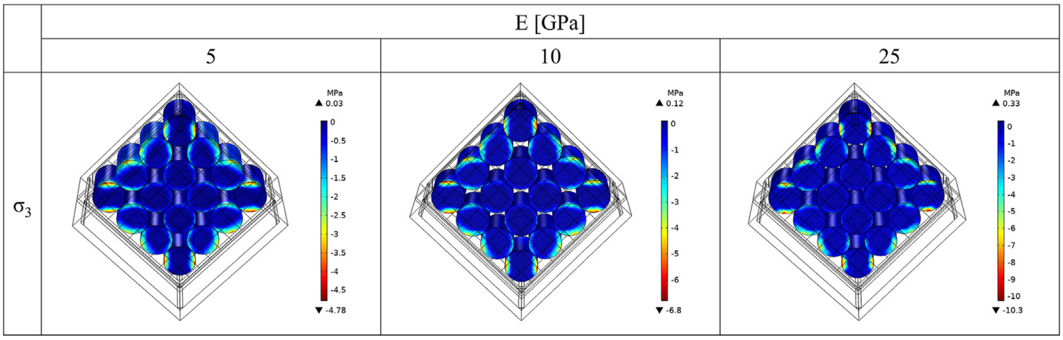


Fig. 11. Maximum uniaxial compressive stress distribution obtained by applying different Young's moduli (5, 10, and 25 GPa). The compressive strength of the waste was set to 10 MPa.

of the reinforced models exhibited the plastic behavior of the container. However, two and three stacks of the reinforced models exhibited the elastic behavior of the container. The fully reinforced container exhibited elastic behavior regardless of the number of reinforced stacks and showed a more stable behavior with the increase in the number of reinforced stacks. For the center and uniformly reinforced design models, tensile stress mainly induced plastic behavior, and parts where the expected tensile stress-induced yielding occurred are shown in Fig. 13.

4. Discussion

Simulation results indicate that the maximum uniaxial compressive stress on the container containing 1000 kg-waste drums at the bottom of the package stack is 11.9 MPa, which is only ~34% of the compressive strength of the container (35 MPa). The maximum strain value is 0.04% and the DP plot shows the elastic behavior. Therefore, the bottom container satisfies the structural stability requirement in terms of stress, strain, and DP plot.

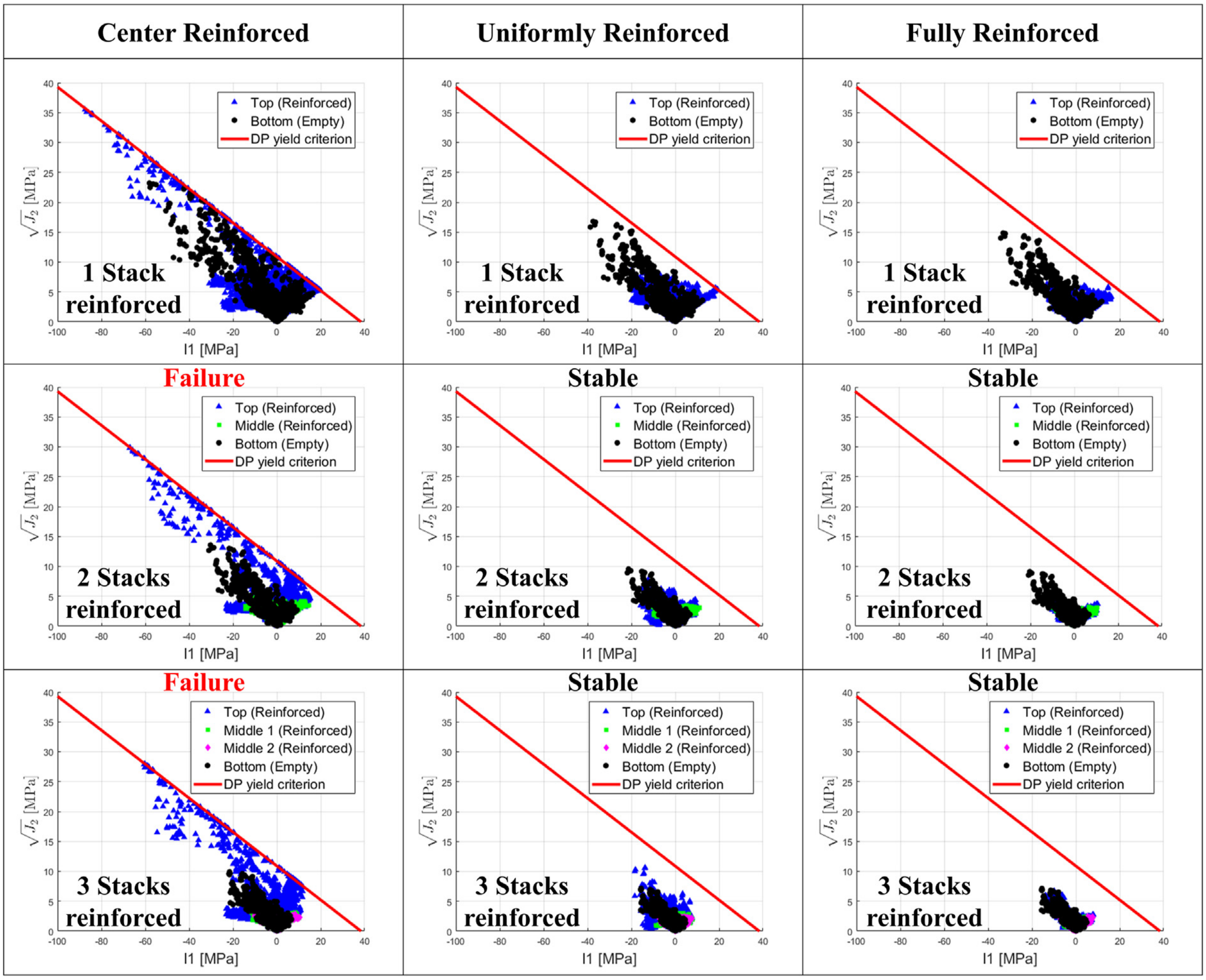


Fig. 12. DP plots of reinforced containers with center, uniformly, and fully reinforced models obtained by varying the number of reinforced stacks.

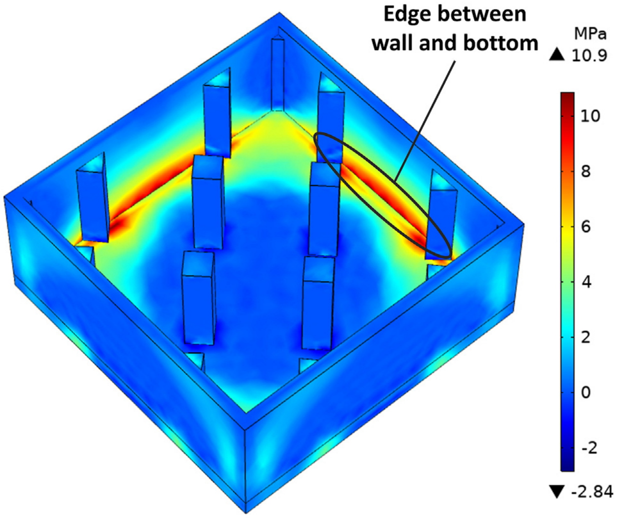


Fig. 13. A tensile dominant part of the reinforced container.

However, the results obtained from the bottom container were completely different compared with that of the top container. This is because a different type of loading was applied to the container; pressure was imposed uniformly on both the lid and wall of the top container via the backfilling material, but it was transferred mainly through the lateral-side wall without bending of the lid.

Only static mechanical behaviors (e.g., elastic or plastic deformation) were considered in the analysis. However, plastic deformation of the concrete by creep could occur under a pressure lower than the yield strength, which is equivalent to the maximum compressive strength in this study. General concrete under 90% continuous pressure of its maximum compressive strength is crushed in 1–2 h, but concrete under 75% continuous pressure of its maximum compressive strength is crushed in 30 years [18]. Therefore, creep should be considered to secure the structural stability of the repository during the operation period and the management period after closure. The compressive strength of concrete should have a safety factor larger than 4/3 of the expected loading as the management period after closure, which is generally longer than 30 years [18]. The bottom container in the reference repository in this study ensures long period stability to creep, since the expected loading is 34% of the compressive strength, such that no creep rupture occurs during the long-term operation period.

The result of Model #2 shows that the top container below ~6% of the expected pressure exhibits structural instability. The expected failure part as a result of stress concentration is the interface between the lid and supporting poles. Stress concentration is expected as the surface area of the supporting pole (24.5 cm^2/pole) is smaller than the area of the lid (6.34 m^2). Although the lid and supporting poles could maintain their stability below ~6% of the pressure, failure occurs under larger pressure before the lid makes contacts with waste as the space between the lid and waste is 6 mm, which is larger than the maximum displacement in the result (1.76 mm). The pressure that is significantly higher than 6% of the expected pressure resulted in non-convergence of the calculation where severe penetration and deformation of the model are expected. These results justify the need for the development of concrete material with higher compressive strength as well as structural reinforcement of the disposal container and enough constraint force of the shotcrete to the backfilling material, which induces load less than 6% of the expected loading.

In Model #3, the situation in which waste inside the container is compressively stressed by the broken lid was modeled using the existing criteria to verify the structural stability. Alternatively, several strengths were applied to the waste to determine the optimized compressive strength that withstands direct pressure without changing the design of the container. From the result, waste with 4 MPa compressive strength, which is larger than the compressive strength criteria of the reference repository, is compressively stressed by a maximum of 10.3 MPa uniaxial compressive stress, and DP plotting showed yielding of the waste and no dependence on Young's modulus. The expected damaged parts are the edges of 12 wastes at the corner of the container. When the waste at the corner is broken, the waste at the center seems to be broken; however, modeling of this waste was not performed in this study.

From the results of the parametric studies, the compressive strength criteria should be enhanced to secure the structural stability of waste disposed of in the reference repository using the existing container design in the Korean repository system. As shown in Fig. 9, the results varied and are highly dependent on Young's modulus when the compressive strength of the waste is 8 MPa. The maximum uniaxial compressive stress increased proportionally with Young's modulus, whereas the strain in the same direction as compression decreased proportionally. Waste with 10 MPa compressive strength exhibited uniaxial compressive stress of less than or equal to its strength in Young's modulus range of 5–25 GPa, and DP plotting also indicated stability. Therefore, it can be deduced that the compressive strength of waste of more than 10 MPa is required to withstand stationary loading in the reference repository without changing the container design, and Young's modulus of the solidified waste, which is difficult to control, could become a controllable parameter in the package design. However, as a result of difficulties in measuring and controlling Young's modulus of the solidified waste by the nuclear-related facility operator, regulating the compression of only the waste that exhibits stability regardless of the value of Young's modulus appears to be more efficient. Moreover, when creep behaviors that affect the structural stability of the container are considered, it may require a compressive strength larger than 15 MPa, considering a safety factor of 4/3. Its safety factor is chosen by considering that the concrete under loading of 75% of its ultimate short time stress took 30 years for failure while design lifetime of disposal container is 60 years [18].

In terms of economic costs, increasing the compressive strength criteria of the waste itself might be difficult considering disposal cost and disposal efficiency. The replacement of existing solidification equipment may be inevitable, and the production of waste may increase significantly when decreasing the waste loading rate to enhance the compressive strength of the waste. Therefore, the mechanical sustainability should be enhanced by reinforcing the existing structural design as performed in Model #4 to mitigate stress concentration due to the pressure applied to the waste or avoid inducing direct pressure to the waste.

In Model #4, the reinforced designs of the disposal container at the top position were modeled to withstand the expected pressure without contact between the lid and the waste. From the result, the center reinforced design with a container exhibited plastic behavior owing to both tensile and compressive stress regardless of the number of reinforced containers at the top position. Therefore, the center-reinforced design is not suitable for the reinforcement of the container. The uniformly reinforced design yielded as a result of the tensile stress. However, when the two containers at the top position are reinforced, structural stability was guaranteed. The fully reinforced design exhibited stability when only one container was reinforced. As the number of reinforced containers increases, the stability of the container increases, as shown in the DP graph. Therefore, the uniformly and fully reinforced designs are considered suitable designs; however, the fully reinforced design showed the best stability as it requires the least number of reinforced container stacks. Therefore, the fully reinforced design is the most suitable design for the reinforcement.

Long-term stability should be considered to secure the structural stability of the disposal container. If the stress applied to the container is less than 75% of the compressive strength, it can maintain its stability for a long period. For the uniformly reinforced design, the maximum compressive stress is 15.3 MPa for two reinforced stacks and 16.3 MPa for three reinforced stacks, which is less than half of the maximum compressive strength of the container. For the fully reinforced design, the maximum compressive stress is 23.7 MPa for one reinforced stack, which is approximately 67% of the compressive strength. The maximum compressive strengths are 14.6 MPa and 9.8 MPa for two and three reinforced stacks, respectively, which are less than 50% of the strength of the container. Therefore, the fully reinforced design exhibits a long period of stability regardless of the number of reinforced stacks. On the other hand, the total weight of the container increases when additional supporting poles are installed; however, the weight increment will hardly affect the result as the maximum stress applied to the bottom is less than 50% of the strength.

From the results of the Model #4, the retrieval of the waste packages already loaded in the silo is not necessary since the reinforcement of only 2–3 containers placed at the top would be enough to secure its structural stability from the static loads from the backfilling materials and the waste packages. The result from the Model #1 also derives the same conclusion since containers below the uppermost container maintain its long-term structural stability under the pressure by the weight of waste packages and backfilling material. In addition, the preparation of the flexible reinforcement plan including the suggested reinforcement in this study is possible as enough time is left to fill the silo with waste packages before closure. Besides, in the case that reinforcement of the container is not considered, the structural failure would be initiated on the uppermost container when the pressure applied on the container lid exceeds 0.015 MPa, 6% of the expected pressure. Once the uppermost disposal container is damaged, the second and third containers could also show structural instability. However, unlike the lid supported by four poles, all the edges of the disposal containers bottom are constrained by the wall and loads would be dispersed to the wall. Thus, the collapse of the whole containers would not be expected, as shown in the result of Model #1. However, apart from being under stress as a result of the backfilling material, the container and drum may be compressively stressed due to additional stress under dynamic forces during an earthquake, transportation, and handling. Other factors such as temperature and geometry of structural steel may affect the result. However, the thermal effect on the concrete in the repository is negligible and the effect of structural steel is negligible as the failure of the container occurs as a result of small supporting poles. Therefore, a safety factor may be required considering dynamic forces, which should be investigated in the future.

5. Conclusion

In this study, the waste package under the expected pressure due to the backfilling material was modeled. The waste package of the reference model exhibited plastic behavior below 6% of the expected pressure, which causes waste to be under direct stress by the lid. Waste with 4 MPa compressive strength, which is close to the compressive strength of the reference model, exhibited plastic behavior regardless of the value of Young's modulus when it is compressively stressed by direct pressure. By enhancing the compressive strength of the waste to 10 MPa, it exhibited elastic behavior regardless of the value of Young's modulus. However, by applying a safety factor of 4/3, which considered the effect of creep, the compressive strength should be larger than 15 MPa. A reinforced waste package was suggested, as enhancing the compressive strength is a large burden for the operator. The result indicates that the fully reinforced design was the most stable and increasing the number of reinforced stacks increased the stability. The reinforced model is under significantly small stress such that the effect of creeping can be neglected. Meanwhile, a safety factor reflecting a dynamic force was not investigated in this study. Therefore, modeling under dynamic force should be considered in future work.

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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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