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ORIGINAL ARTICLE

Field-derived unit area debris values for earthquake waste assessment: implications from the 2023 earthquakes in Turkey

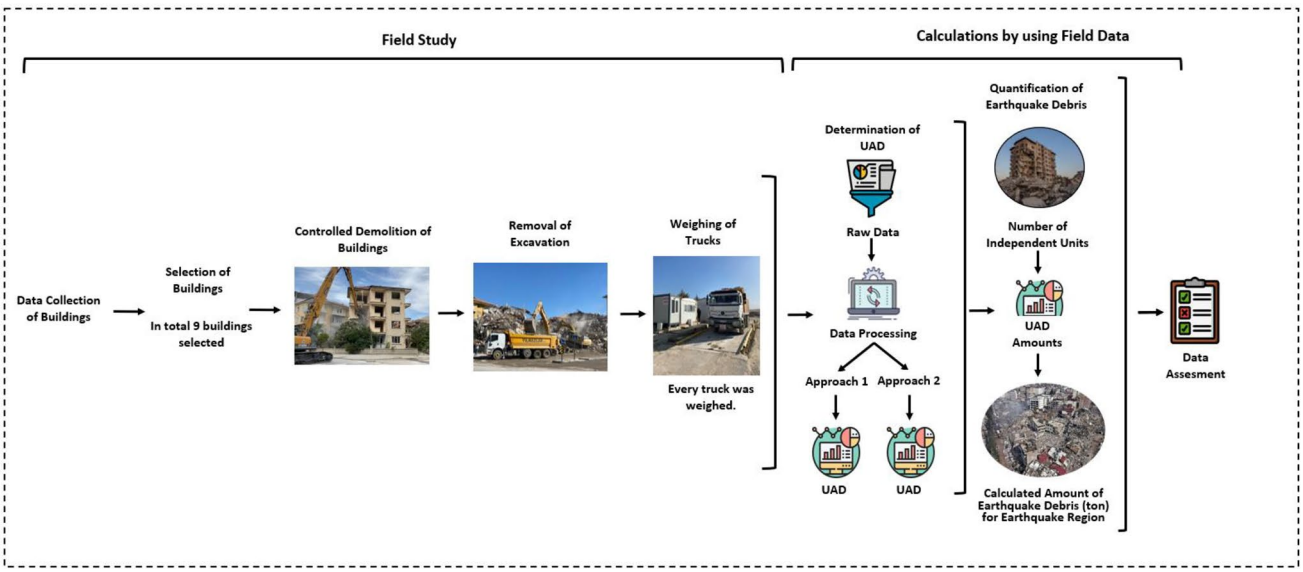
Kadir Özçelik[1] · Ali Tamer Çetinkaya[1] · Kadriye Elif Maçin[1] · Hüseyin Güven[1] · Mahmut Altınbaş[1] · Mehmet Zeki Duman[2] · Osman Atilla Arıkan[1]

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Abstract

This study determines unit area debris (UAD) and earthquake waste amounts following the February 6, 2023, Earthquakes in Turkey. A field study was conducted in Malatya, one of the eleven cities severely affected by the earthquakes. The research involved the selection of residential reinforced concrete (RC) buildings, demolition of buildings, debris removal, and weighing debris trucks to calculate UAD values for structures categorized into three construction periods: ≤1999, 2000–2010, and 2011–2018. The UAD values were estimated using two field-based approaches developed to correct for debris originating from basement filling: Approach 1 determined the basement filling contribution through direct field observations, while Approach 2 quantified it via structural calculations. Approach 1 yielded average values of 0.845, 0.952, and 1.009 tons/m^2, while Approach 2 resulted in 0.933, 0.979, and 1.107 tons/m^2 for the respective periods. Based on these findings, earthquake debris generation was estimated to range from 93.9 to 159.3 million tons across the affected region, with the highest amounts occurring in Hatay, Kahramanmaraş and Malatya. These results highlight UAD's importance for estimating waste across varying seismic codes. Further research into material properties and construction techniques will provide valuable insights for minimizing future debris generation.

Graphical abstract



Keywords Demolition waste · Field study · Earthquake debris · Seismic codes · Waste generation

Extended author information available on the last page of the article

Introduction

The amount of debris generated by earthquakes often exceeds the annual municipal solid waste (MSW) generation in affected regions by a significant margin, highlighting a critical challenge for disaster management and recovery efforts [1]. According to Chandrappa and Das [2], over the past 110 years, a total of 1,190 earthquakes have been reported, including those that occurred at sea and triggered tsunamis, resulting in the deaths of more than 2.5 million people and affecting 170 million individuals worldwide. In 1995, the Kobe earthquake in Japan caused approximately 6,400 deaths, destroyed 256,000 dwellings, and generated around 15 million tons of debris [3]. Additionally, the 2010 7.0-magnitude earthquake in Haiti produced an estimated 52 million tons of waste, underscoring the extensive waste generated by such disasters [4]. The Great East Japan Earthquake in 2011 resulted in approximately 16,000 deaths, the destruction of 1.1 million buildings, and up to 28 million tons of disaster waste [5]. Similarly, the 2015 Nepal–Gorkha earthquake produced an estimated 13.8 million tons of debris. Such volumes often exceed the capacity of existing solid waste management facilities and human resources [6].

Earthquakes can impact extensive regions depending on their magnitude. Debris estimation methods often rely on the degree of building damage; for example, hazard maps have been applied to predict debris volumes associated with potential building collapses [7]. Studies on disaster waste management emphasize the importance of accurately estimating debris quantities to enable effective waste management and recovery efforts [8]. Federal Emergency Management Agency's (FEMA) Debris Estimating Field Guide states that the methods for debris amount estimation should be selected based on the accuracy and precision requirements of the estimate [9]. Three different methods stand out. First, field measurements of debris can be taken to develop estimates, using visual observation and detailed data collection with equipment such as measuring tapes and GPS units. Second, aerial and satellite imagery allow rapid analysis of large areas. Third, computer models produce estimates using historical disaster data, geographic information systems, and variables related to the magnitude of the disaster. "Ground measurement" includes observation and direct measurement of debris quantities on-site after a disaster. Although this method generally provides more accurate data than other estimation techniques, it requires more time and labor [9]. Previous studies generally identify two primary approaches for determining the basic unit of disaster debris quantification: (1) analyzing waste disposal data from large-scale disasters, and (2) measuring demolition waste generated during building tear-downs. For instance, the Ministry of Environment Japan [10] used the first approach to estimate a post-disaster waste generation rate of 117 tons per building following the Great East Japan Earthquake. In such cases, estimating earthquake-induced waste requires detailed information on affected buildings, including the number of units, floor area, construction materials, and construction year. Therefore, determining unit area debris (UAD) is essential for accurately predicting earthquake-related waste generation. Demolition waste is typically calculated by multiplying the construction area by the average unit area waste generation rate (ton/m^2). For example, Xiao et al. [11] reported demolition waste quantities generation rates ranging from 0.8 to 1.3 tons/m^2. In Japan, waste generation rates have been reported to range from 0.40–0.61 tons/m^2 for wooden houses and approximately 0.85 tons/m^2 for reinforced concrete (RC) buildings [12]. Structural characteristics, such as framing type, further influence debris quantities; wood-frame buildings generally produce less waste than concrete-frame structures. Cochran et al. [13] summarized waste generation rates per unit area across different residential construction and demolition types by building frame material, including wood and concrete. Another study by Poudel et al. [14] analyzed 13 buildings for different construction types to quantify after the Gorkha earthquake by highlighting including and excluding foundation on UAD amount from buildings. Poon [15] conducted studies on buildings from different construction periods having different numbers of stories to quantify demolition waste in Hong Kong. The calculations utilized the average floor ratios derived from the selected cut-offs [15]. During demolition, construction materials undergo fragmentation and lose their compact in-situ structure, resulting in a loose debris matrix with significant inter-particle voids. This increases bulk volume, commonly referred to as the bulking effect, a critical factor in debris volume estimation [16]. The expansion of debris volume following mechanical demolition, characterized by the formation of voids between rubble particles, was accounted for using transformation coefficients as defined by Solis-Guzmán et al. [17]. Their model suggests that RC and masonry elements experience a 30%-40% increase in volume during demolition. Tanikawa et al. [18] stated that safety factors include unaccounted architectural finishes, ensuring that the calculated UAD values represent a realistic mass balance between the original structure and the generated waste amounts. Yang [19] highlights that inert materials account for approximately 96% of earthquake demolition waste by volume. These particles have more angular, rougher surface textures than natural soils, and this irregular geometry results in a significantly higher void ratio in the waste bulk. The literature review indicated that the UAD value, building structure, and building type are among the key parameters for estimating earthquake debris.

The southeastern region of Turkey experienced two major earthquakes on February 6, 2023, which caused severe damage across 11 cities in 13 affected provinces. Widespread destruction was reported in Hatay, Kahramanmaraş, Malatya, Adıyaman, Gaziantep, Diyarbakır, Osmaniye, Adana, Şanlıurfa, Elazığ, Kilis, Kayseri, and Niğde (Fig. 1). According to the Presidency of the Republic of Turkey Strategy and Budget Office (SBO), the earthquakes affected 14 million people in the region, representing 16.4% of Turkey's total population of 85.7 million [20]. Given the scale of the earthquakes and the large number of people affected, managing earthquake debris is expected to be a major challenge. The Ministry of Environment, Urbanization, and Climate Change of Turkey (MoEUCC) announced that 279,000 buildings and 821,302 independent units sustained damage requiring demolition [21]. According to the SBO, 43.5% of the affected buildings were constructed ≤ 1999, 47.4% after 2000, while the construction year of the remaining 9.1% was unknown [20].

Turkey's building stock can be classified into three construction periods: ≤ 1999, 2000–2010, and 2011–2018. These periods correspond to major milestones in the country's seismic design and construction practices. The year 2000 represents a critical transition point, reflecting the implementation of the 1998 Turkish Earthquake Code, the incorporation of lessons learned from the 1999 Kocaeli and Düzce earthquakes, and the revision of Design and Construction Rules for Reinforced Concrete Structures (TS 500) for RC design in 2000. This period also shows the widespread adoption of ready-mix concrete and deformed reinforcement bars. Although the Building Inspection Law was issued in 2001 and initially applied only to pilot provinces, its nationwide implementation in 2011 marks the beginning of the third construction period (2011–2018). Buildings constructed during this period were subject to mandatory nationwide inspection and an updated seismic regulatory framework published on March 18, 2018 [22, 23]. Accordingly, the buildings were categorized into three groups: those constructed on or before 1999 under the provisions of the 1975 seismic code; those built between 2000 and 2010 following the post-1999 regulatory revisions; and those constructed between 2011 and 2018 under mandatory building inspection requirements. One of the most significant developments in seismic design was the introduction of performance-based design and advanced seismic analysis procedures in the 2018 TBEC. Earlier regulations, including the 1975 and 2001 codes, primarily focused on ensuring that structures could withstand specific seismic loads. In contrast, the 2018 TBEC explicitly defines target performance levels for buildings following an earthquake, such as collapse prevention, life safety, and continued operation. Therefore, understanding the characteristics and age distribution of the building stock in earthquake-prone zones is essential for forecasting the potential amounts of demolition waste generated by future earthquakes.

Xiao et al. [11] estimated the earthquake demolition waste generated after the February 6, 2023, earthquakes in Turkey using two approaches-one based on population and average residential area per person, and the other based on the number and type of damaged buildings-resulting in an estimated range of 450–20 million tons. In contrast, the United Nations Development Program (UNDP) reported that the earthquakes generated between 116 and 210 million tons of debris [24]. In addition, Temelli et al. [25] estimated that the total waste generation for the Kahramanmaras earthquakes was 396 million tons. According to SBO estimates, the total volume of construction and demolition waste is expected to be between 100 and 120 million cubic meters [20]. These studies highlight substantial variability in estimated debris quantities, largely due to differences in



Fig. 1 13 provinces affected by the earthquakes on February 6, 2023, in Turkey. Earthquake epicenters and magnitudes; Blue: 6 February 2023 (01:17, UTC), Mw=7.7, Red: 6 February 2023 (10:24 UTC), Mw=7.6

underlying assumptions and reliance on literature-based UAD values rather than field-derived data. To address this gap, this study employs a comprehensive, field-based methodology designed to produce estimates that closely reflect actual post-earthquake conditions. The approach integrates primary data from on-site measurements with calculations supported by relevant literature. The objectives of the study is threefold: (i) to examine how debris quantities vary across buildings constructed under different versions of the Turkish Building Earthquake Code (TBEC), (ii) to estimate post-earthquake debris generation per unit area in Turkey to support effective waste management planning, and (iii) to estimate the total debris generated in earthquake-affected cities. By determining debris quantities per unit area and estimating overall debris generation, this study addresses future needs in the event of potential earthquakes. Furthermore, it provides valuable information for authorities, such as municipalities and national agencies, regarding potential landfilling requirements and the scale of the earthquake debris management. In this context, the study represents a significant step toward improving understanding of post-earthquake debris generation in earthquake-prone regions and may serve as a reference for future research.

Materials and methods

Study area

A field study was conducted in Malatya Province, one of the cities heavily affected by the earthquakes. This city was selected due to its proximity to the epicenter of the second earthquake that occurred on February 6th (Fig. 1, red dot). Additionally, it was selected because the city where "controlled demolition" and debris management were carried out in the most organized way after earthquakes. Controlled demolition is a planned process for demolishing a structure to minimize environmental damage, noise, and risk.

The research was carried out in three main phases (Fig. 2). The initial phase of the study involved collecting buildings' data from relevant Local Governments/District Municipalities. The second phase focused on assessing the UAD amount through on-site demolition. Controlled demolition of the selected buildings was carried out. During demolition, after the debris was collected, the trucks carrying the material were weighed to determine the amount of demolition debris. Two different approaches were applied to determine the UAD. Using these two approaches ensures validation and reliability for the two different UAD amounts in tons/m^2. The final phase combines the obtained UAD coefficients with the demolished independent numbers to calculate the total amount of earthquake debris. For this purpose, data on the number of independent units were obtained from the MoEUCC. The Gross area of independent units (two different alternatives) for the relevant region was determined. A total of six scenarios were developed by combining the UAD coefficient (tons/m^2) derived from Phase 2 (approach results) with average values reported in the literature. Ultimately, these combinations of scenarios yield the estimated quantity of earthquake debris waste (tons) for the region.

Data collection and selection of buildings

This phase of the study involved collecting building data from local/district municipalities. These municipalities have a demolition plan for each building requiring demolition. Information on the buildings was obtained from the Yeşilyurt District Municipality and the Battalgazi District Municipality based on their location. Severely damaged RC buildings are located in groups in different neighborhoods. The administration's demolition plan was followed. Therefore, severely damaged RC residential buildings that required demolition were selected for the study. The focus on residential typologies was to ensure consistency in structural parameters, as public or commercial buildings often show different occupancy-based design standards and material intensities, which could lead to significant variations in debris generation rates [14]. The selection of buildings was based on the collected information. This information covers structural parameters such as the structural project plan, year of construction, gross area, location, building material, and number of independent units. First, the year of construction was important to observe the impact of TBEC on Turkey's building stock and UAD amounts. The study examined the impact of evolving earthquake regulations on UAD by categorizing Turkey's building stock into three construction periods: ≤ 1999, 2000–2010, and 2011–2018. Furthermore, the structural plan, gross area, location, and number of independent units of the buildings were collected to provide a better understanding of the UAD amounts. A total of nine buildings were selected, three from each category, to provide statistical data for comparison of the building-based UAD value (Fig. S1). The presence of basements and the foundation structure of some buildings for different purposes, such as storage, was examined. Although the sample consisted of nine buildings, it represents a substantial empirical effort under post-disaster conditions where gravimetric debris measurements are constrained by safety considerations, site accessibility, and demolition schedules. Therefore, a purposive sampling strategy was adopted to ensure the appropriateness of the selected sample with respect to the study's objectives. The selected samples represent three critical seismic code eras in Turkey, ensuring the derived UAD values capture realistic variations in structural materials.

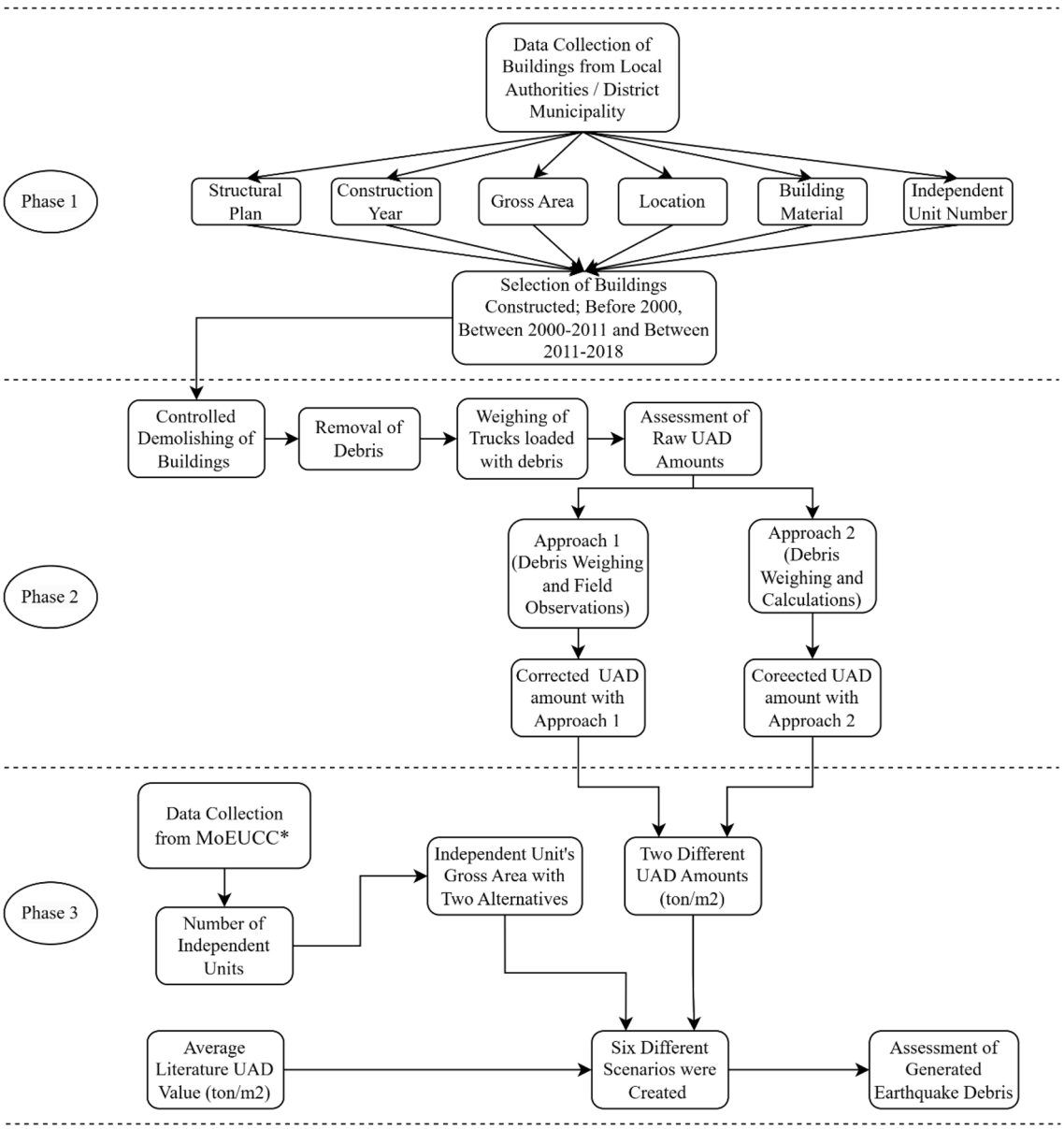


Fig. 2 Methodology of the study. *Ministry of environment, urbanization, and climate change (MoEUCC) of the Republic of Turkey

Furthermore, structural variability among the selected buildings, including differences in gross floor area, number of floors, foundation types, and the presence of basements, was recorded. This approach reflects the heterogeneity of the urban building stock and enhances the representativeness of the sample in terms of typical RC residential buildings in the affected region. For the representativeness, buildings with similar RC structures were selected. Before 2000 (≤1999) buildings all had four floors but varied in gross area; for instance, buildings 1 and 3 shared the same structural plan but differed in size. Among buildings constructed between 2000 and 2010, building 4 has five floors, while the others have four; buildings 4 and 6 included basements, whereas building 5 did not. For buildings constructed between 2011 and 2018, buildings 7 and 8 have basements, mat foundations, and seven and eight floors, respectively, while building 9 has column footings similar to pre-2011 structures.

Assessment of unit area debris (UAD) amounts

In Phase 2, contracted firms carried out controlled demolitions of the selected buildings. For safety reasons, foundations were left intact, and the debris from the buildings was used to fill the basements. The use of on-site debris for backfilling is a standard practice in Turkey to ensure soil stability and public safety after demolitions. Mechanical demolition using excavators was carried out by the contractor firms for all selected buildings. Before demolition,

the homeowners took household appliances and personal belongings. In addition, field observations revealed that most non-structural recyclables (e.g., windows and glass) had already been removed by homeowners for the second-hand market, as evidenced by Fig. S2. Therefore, only the RC structure and roof of the buildings were demolished (Fig. S2). To evaluate the potential impact of non-structural components (e.g., household goods, textiles, and electronics) on UAD amounts, a preliminary waste characterization study was conducted in a≤1999 building containing personal belongings. The characterization of the 10% (as mass) of the total demolition waste from this building showed the following mass-based composition: Debris (rubble, concrete, bricks, etc.): 94.8%, Iron: 2.3%. Non-structural items (Total∼2.9%): Including Metals & Electronics (1.1%), Wood (0.98%), Plastic (0.34%), Textiles (0.31%), Paper & Cardboard (0.1%), and Bulky items (0.1%). These results demonstrate that even when belongings are present, they account for less than 3% of the total weight, which is within the negligible margin of error for large-scale debris estimation.

The operational methodology of demolition contractors plays a critical role in backfilling and debris management. During the field study, observations revealed that the contractor's business model often determines the "destination" of the debris. When contractors are compensated primarily by the value of recycled iron, they tend to transport heavy structural elements (columns and beams) to storage sites to facilitate the efficient separation of iron from concrete. This results in a higher percentage of debris being sent to the storage site. When contractors are paid based on the demolished floor area, they prioritize minimizing transportation costs (fuel, labor, and number of truck trips). In these cases, they use as much heavy structural debris as possible to fill on-site basement voids, resulting in a lower percentage of debris sent to the storage site. After demolition, the excavated rubble was removed (Fig. S3, S4). The same trucks were used to remove rubble from each building. Each truck was first weighed empty. The loaded trucks were then weighed, and the net rubble amount was calculated from the difference between the loaded and empty weights, using the weighbridge receipt (Fig. S5). The total net rubble removed from each truck was calculated to determine the total rubble amount from the controlled demolition of each building. Filling the basements and leaving the building's foundations required the development of different approaches to UAD calculations. After weighing the total rubble amounts from the demolished buildings, the resulting data was combined with the total gross area of each building to calculate the raw UAD amounts. Raw UAD quantities represent values that account only for the total weighed debris from demolished buildings. The building foundations and filled basements will be removed later, at the discretion of the competent authority. Therefore, after obtaining the total debris quantities and total gross area for each building, UAD quantities were calculated in ton/m^2 using two different approaches due to the practice of filling basements and leaving the foundations.

Approach 1: combination of debris weighing data and observations in the field

This approach utilizes structural plans and field observations to account for the residual debris used as backfill. To ensure accuracy, site-specific correction factors were developed to represent the partitioning of mass between debris transported to storage sites and material retained for on-site backfilling. The UAD generated by the selected buildings was estimated by integrating empirical weighbridge data with the mass of structural elements remaining on-site, such as foundations and basement floors. The implementation of site-specific correction factors was necessary to distinguish between the amount of debris transported to the storage site and that retained for backfilling. These factors were derived by comparing the theoretical structural data (from the structural project), contractors' logs, and the empirical weighbridge data. Field observations revealed that this partitioning is significantly dictated by the building's design and the volumetric capacity of its underground structures. This approach is consistent with material flow-based estimation methodologies widely used in construction and demolition waste studies, where total material quantities are partitioned into transported and retained fractions [26]. The retained debris fraction was physically constrained by the volumetric capacity of underground structures, ensuring consistency with structural mass balance and preventing overestimation of total debris quantities. The observed correction factors are further supported by the structural characteristics of RC buildings designed in accordance with the Turkish seismic code. In such buildings, a significant proportion of the total structural mass is concentrated in foundations, basement slabs, and vertical load-resisting elements such as shear walls. This results in a substantial fraction of the building mass being located at or below ground level, thereby increasing the capacity for on-site retention of demolition debris during controlled demolition.

The aforementioned preliminary study (Sect. 2.3) was also conducted to evaluate and validate the physical basis of the correction factors used in Approach 1 for representative basement-free RC buildings. For this≤1999 building, the measured transported debris (1,102 tons) corresponds to 80% of the total structural mass, yielding a residual on-site mass of 275.5 tons. This residual mass was independently verified using structural project data, in which

the foundation system (strip footings, tie beams, and lean concrete) was quantified at approximately 114 m^3, corresponding to 273.6 tons, assuming a unit weight of 2.4 ton/m^3. The good agreement (< 1% deviation) confirms that the 80% coefficient reflects a physically consistent partitioning of structural mass rather than an empirical assumption (detailed calculations and supporting data were provided in the Supplementary Material).

Based on the integration of field measurements and structural constraints, buildings constructed ≤ 1999 and between 2000 and 2010 exhibited transported-debris fractions of approximately 65–75%, leading to the adoption of a representative value of 70%. In contrast, buildings constructed between 2011 and 2018, particularly those with mat foundations and multiple basement levels, showed significantly lower transported fractions. Field observations and structural assessments indicated that these underground structures can accommodate a considerable portion of the generated debris, resulting in transported fractions of approximately 35–40% (represented as 37%). These representative values correspond to the central tendency of the observed ranges across the dataset and are therefore used as characteristic values for each structural category.

For buildings constructed ≤ 1999 and between 2000 and 2010, a baseline factor of 70% was generally used to represent the fraction sent to storage sites. In contrast, for high-rise structures built between 2011 and 2018 (e.g., Buildings 7 and 8), the factor was significantly lower at 37%. This divergence is attributed to modern engineering designs featuring extensive mat foundations and multiple basement levels. Following strict safety protocols, these large underground structures were used as backfill for the building's masonry and concrete rubble. On-site measurements and contractor logs verified that these basement capacities could accommodate approximately 63% of the total generated mass, leaving only the remaining 37% to be transported off-site. Beyond structural capacity, field observations indicated that debris partitioning is heavily influenced by contractors' business models and economic incentives. In contracts where the primary profit was derived from iron recovery from structural elements with high reinforcement density, it was prioritized for transport to storage sites for further processing. This practice increased the fraction that was sent to the landfill. Conversely, when contracts were based on the demolition area, firms aimed to minimize transportation and logistics overhead. In these cases, contractors tried to maximize the use of heavy rubble and reinforcement for on-site backfilling, significantly reducing the amount of weighed debris. The application of these operational and structural realities resulted in the following case-specific distributions. For the period of ≤ 1999, buildings 1 and 3, 70% of the debris was landfilled. However, building 2, which lacked a basement, resulted in 80% of the total mass being sent to the storage site. Between 2000 and 2010, buildings 4 and 6 adhered to the 70% landfilling ratio. Building 5, which lacks a basement, contributed 80% of its total weighed debris to the storage site. 2011–2018 Period: Buildings 7 and 8, featuring seven and eight floors with mat foundations, utilized the majority of their rubble for backfilling, resulting in only 37% of the debris being transported. Building 9, despite being in this category, featured a column footing foundation and a basement. Field data and contractor logs indicated that a substantial portion of the rubble was used as backfill, resulting in a landfill-bound fraction of approximately 50%. The adopted correction factors constitute site-specific; however, physically constrained and empirically supported estimates, derived from the integration of multiple independent data sources and aligned with established material flow-based approaches in construction and demolition waste studies. A sensitivity analysis was conducted by varying the correction factors by ± 10%, confirming that the overall trends in UAD values remained unchanged.

The equations used to calculate the UAD amount are given below.

$$UAD = TDA/GA \tag{1}$$

In Eq. 1, the abbreviations *"UAD", "TDA*", and "*GA*" represent "Unit Area Debris amount (ton/m^2)", "Total Debris Amount (ton)", and "Gross Area (m^2)", respectively. The general formula for UAD calculation is given below.

In Approach 1, corrected UAD amounts of buildings, shown in Eq. 2.

$$UAD = \frac{\left(\frac{TDA}{CorrectionFactor}\right)}{GA} \tag{2}$$

Approach 2: combination of debris weighing data and calculations based on structural project

Approach 2 calculates the remaining debris volume within the foundation and basement levels, serving as the basis for structural analyses. In addition to the debris quantities weighed by loaded trucks, the UAD was calculated. This was achieved using the total gross area allocated for the excavated debris and incorporating the data presented in Table 1. The parameters in Table 1 represent the physical transformation of building materials during demolition. The debris expansion rate (E) of 1.5 accounts for the conversion of solid structural volume into loose material. The Void Ratio (v) of 0.2 characterizes the effective density of this rubble when utilized as basement backfill. These factors, combined with a Safety Coefficient (SF) of 1.2, include

Table 1 Assumptions for the calculation of UAD amounts in Approach 2

Abbreviation	Definition	Value
H	Floor height (m)	Taken from the structural plans
SF	Safety coefficient	1.2
v	Ratio of void volume/debris volume	0.2
E	Debris expansion rate	1.5
WD	Waste density (ton/m^3)	1.6

unaccounted architectural finishes. A waste density of 1.6 ton/m^3, as reported by Maçin and Demir (2018) for Turkey [27], was adopted for this assessment. Buildings constructed up until 2011 had spread footings; these were not considered separately and were included in the basement area calculation. For these specific buildings, the remaining excavation volume was adjusted by multiplying the building base capacity by the values specified in Table 1. Furthermore, in these post-2011 structures, the RC bearing weight was incorporated into the basement floors, consistent with the foundation requirements detailed in the building's structural projects.

Equation 3 shows the calculations for the second approach. In this method, the total amount of debris was determined by combining data on the weighed debris amount with calculations based on the building's structural plan. The total amount of debris was then determined by dividing this value by the GA, resulting in the UAD amount.

$$UAD = \frac{(TDA + (HxGAxSFxvxExWD))}{GA} \quad (3)$$

Assessment of the amount of generated earthquake debris

In this part, after assessing the UAD amounts for the buildings, debris calculations were performed to estimate the generation of earthquake-induced demolition waste in the region. The calculations were based on the number of independent units as provided by the MoEUCC [21]. The earthquake debris from buildings was calculated in tons using the gross area and UAD of independent units. Initially, the UAD values for the nine selected buildings were determined using their actual gross floor areas, as obtained from structural project plans. Subsequently, to estimate total debris quantities at a city scale, representative area scenarios were required. Since the aggregate disaster data provided by the MoEUCC only specifies the number of independent units rather than specific building dimensions, two benchmarks-120 m^2 and 150 m^2-were adopted to reflect the regional building typology. These values were chosen based on the sociocultural and architectural characteristics of Southeastern Turkey. While the national average net residential area is reported as 114 m^2 [28], the transition to gross area (accounting for balconies, stairwells, and common spaces) requires higher parameters. As established in the literature, gross floor area is the summation of individual floor areas, including structural elements. In this region, residential units are typically larger than those in Western provinces [29]. Field observations in the disaster zone indicated that these two scenarios provide a realistic range of estimates that captures regional variations and the material properties of the affected building stock. Moreover, the UAD values found in this study and in the literature were used to calculate earthquake-induced waste generation. The average literature value was obtained from different case studies. In addition, to be able to compare and discuss the results of this study, only RC structures' (residential buildings') UAD data were collected from the literature. The calculations are outlined in Fig. 2. Six scenarios were created using two gross area values and three UAD amounts to estimate the earthquake debris generated in the region. Developed scenarios applying the stages of the calculation method are given in Table 2.

Table 2 The developed scenarios

Scenario number	Unit gross area (m^2)	Unit area debris (ton/m^2)
SC-1	120	Approach 1
SC-2	120	Approach 2
SC-3	120	Average literature value
SC-4	150	Approach 1
SC-5	150	Approach 2
SC-6	150	Average Literature value

In Eq. 4, the abbreviations *"UGA"*, "UAD", and "W" were used to represent "unit gross area", "unit area debris," and "total earthquake debris amount (ton)" respectively. In addition, "*n*" represents the total number of independent units demolished during and after earthquakes due to severe damage.

$$W = nxUGAxUAD \quad (4)$$

The results of Eq. 4 were used to determine the total amount of waste generated in the region. Additionally, each scenario was compared with the others in terms of the amount of earthquake waste generated in the region.

Results and discussion

This study estimated earthquake debris generation in the region using UAD values. The raw UAD data for the selected buildings (B1 to B9) is presented in Table 3. Although B1 and B3 were structurally similar and the demolition produced similar amounts of rubble, the UAD was low because the gross area of B3 was 1.6 times that of B1. It was expected that the UAD values of recently constructed buildings (especially those built between 2011 and 2018) might be higher due to the use of more durable structural materials [1]. However, the current practices applied during demolition showed that a considerable amount of debris was used to fill basements.

According to the field study, there is a correlation between building characteristics and the debris landfilling ratio due to the weighing of the total debris amounts from buildings sent to the storage site. The proportion of demolition debris sent to the storage site was strongly influenced by the presence of a basement and the subsequent on-site reuse of rubble for backfilling. Buildings constructed before 2011 (B1, B3, B4, and B6) generally had 70% of their total debris sent to the landfill. Buildings lacking a basement (B2 and B5) consistently showed a higher proportion, with 80% of the total weighed debris being landfilled. For buildings constructed between 2011 and 2018 (B7 and B8) that included basements and mat foundations, the substantial use of debris for basement filling resulted in a significant decrease in the landfilled amount to approximately 37% of the total. Building 9, also constructed between 2011 and 2018 with a basement and a column footing foundation, utilized a substantial amount of rubble for basement filling, leading to an intermediate landfill proportion of approximately 50%.

This analysis highlights that on-site debris reuse for basement filling and leaving the foundation in place is the primary mechanism for reducing the amount of raw UAD. Therefore, the raw data required correction for this study, based on field observations (Approach 1) and calculations (Approach 2). In this case, Approach 1 and Approach 2 were applied to the raw data (Table 3). The corrected UAD values determined by Approach 1 and Approach 2 for the buildings (B1 to B9) constructed across three periods: ≤1999, from 2000 to 2010, and from 2011 to 2018 are given in Table 4.

Table 3 The raw UAD amounts originated from buildings

Building Construction Year	Building Code	UAD (ton/m^2)	Ave ± std dev. (ton/m^2)
Before 2000 (≤1999)	B1	0.647	0.626 ± 0.17
	B2	0.828	
	B3	0.402	
2000–2010	B4	0.615	0.701 ± 0.90
	B5	0.818	
	B6	0.669	
2011–2018	B7	0.402	0.476 ± 0.11
	B8	0.396	
	B9	0.631	
Total			**0.601 ± 0.09**

A comparison of Tables 3 and 4 showed that filling the basements and leaving the buildings' foundations had a significant effect on the UAD amounts, even though all these buildings were RC structures. Based on Approach 1, buildings constructed≤1999 had the lowest UAD value of 0.845 ± 0.20 tons/m^2, followed by those built between 2000 and 2010, at 0.952 ± 0.06 tons/m^2. The buildings constructed from 2011 to 2018 exhibited the highest UAD value of 1.009 ± 0.08 tons/m^2. The overall UAD value for Approach 1 was 0.936 ± 0.07 tons/m^2. A similar trend was observed in Approach 2. Buildings constructed≤1999 had a UAD value of 0.933 ± 0.15 tons/m^2, while those built from 2000 to 2011 had a value of 0.979 ± 0.07 tons/m^2. The highest value, 1.107 ± 0.05 tons/m^2, was determined for buildings constructed between 2011 and 2018. The overall UAD value for Approach 2 was 1.007 ± 0.07 tons/m^2. The findings reveal an upward trend in UAD values corresponding to newer construction periods, with UAD values ranging from 0.845 to 1.107 tons/m^2. The gradual increase in

Table 4 Corrected UAD amounts of the buildings with approach 1 and 2

Building Construction Year	Building Code	Approach 1, UAD (ton/m^2)	Ave ± std dev. (ton/m^2)	Approach 2, UAD (ton/m^2)	Ave ± std dev. (ton/m^2)	Average of Approach 1 and 2 (ton/m^2)
Before 2000 (≤1999)	B1	0.925	0.845 ± 0.20	0.979	0.933 ± 0.15	0.880
	B2	1.035		1.087		
	B3	0.575		0.734		
2000–2010	B4	0.879	0.952 ± 0.06	0.88	0.979 ± 0.07	
	B5	1.023		1.058		0.966
	B6	0.955		1.000		
2011–2018	B7	1.072	1.009 ± 0.08	1.178	1.107 ± 0.05	
	B8	1.055		1.074		1.058
	B9	0.901		1.069		
Total			**0.936 ± 0.07**		**1.007 ± 0.07**	

corrected UAD values, ranging from 0.845 to 1.107 tons/m^2 across the studied construction periods, is primarily driven by evolving seismic regulations and the resulting shifts in structural material properties, rather than by a simple change in material strength. As building codes in Turkey evolved—particularly after the 1999 earthquakes—the seismic design requirements became more stringent. This led to the adoption of larger structural cross-sections, higher reinforcement ratios, and more robust foundation systems. As noted by Townsend and Anshassi [16], debris composition is a direct reflection of the building codes in effect during a structure's construction. A critical factor in this trend is the transition from the Working Stress Method (WSM), prevalent in ≤ 1999 structures, to Limit State Design (LSM). While LSM typically allows for more optimized, slenderer superstructure sections than the thicker, less economical sections of the WSM era (≤ 1999), the total structural mass of newer buildings in Turkey has increased significantly under new seismic codes. This increase is largely attributed to the widespread adoption of massive mat foundations and increased shear wall density mandated to ensure structural resilience. Consequently, the observed UAD growth is not merely a result of material properties but represents a combined effect of total structural mass and the transition to more robust foundation systems. As demonstrated by the divergence between raw and corrected data, a substantial portion of this additional mass in newer buildings remains on-site as foundation elements or basement backfill. By utilizing site-specific correction factors that account for operational diversity and contractual logistics, the corrected UAD values reveal the higher structural intensity inherent in modern, safer construction practices. Field observations during the controlled mechanical demolition of the selected buildings provided further insights into the evolution of structural resilience. Although all nine buildings were severely damaged, none collapsed during the seismic event. However, the effort required for demolition varied significantly by construction period. The ≤ 1999 buildings were demolished with relatively low mechanical effort, whereas the post-2011 buildings exhibited substantial resistance to excavators. This increased demolition difficulty in newer structures is a tangible result of higher concrete classes, denser reinforcement ratios, and the mandatory use of shear walls required by modern seismic codes. These observations underscore the importance of code implementation. At the same time, more robust designs lead to higher material densities and UAD values; they help ensure that buildings maintain their structural integrity and prevent catastrophic collapse, thereby directly contributing to safer urban environments. The UAD generation rates from the literature were obtained and listed alphabetically in Table 5.

Table 5 The UAD range and average values were obtained from the literature

Region/Country	UAD range (ton/m^2)	Average UAD amount (ton/m^2)	Reference
China	0.80—1.30	1.05	[11, 30]
China		1.36	[31]
China	1.46–1.57	1.52	[32]
China/Shanghai	1.19–1.61	1.40	[32]
Denmark	1.00–2.00	1.50	[33]
European Union	0.81 – 1.37	1.09	[32]
Iran		1.75	[25]
Japan	-	0.85	[12]
Japan	-	1.11	[5]
Kuwait		1.45	[34]
Malaysia		1.04	[35]
Nepal	1.50–2.74	2.10	[25]
Norway	0.58 – 1.10	0.84	[36]
Portugal		1.27	[37]
Portugal	1.05–3.59	2.32	[38]
Spain	0.80—1.00	0.90	[39]
Spain		1.13	[40, 41]
Spain/Galicia		1.35	[42]
Turkey		**1.37**	[25]
Turkey		**0.94**	**This study: Approach 1**
Turkey		**1.00**	**This study: Approach 2**
USA		0.91	[13]
USA		0.83	[16]
Average		**1.27**	

The UAD amount varies significantly across the globe. Table 5 reveals significant variations across locations, which can be attributed to differences in construction practices, the variety of building materials used, and urban density. The UAD amounts typically range between 0.58 and 3.59 ton/m^2, with an average of approximately 1.27 ton/m^2. Asian countries such as China, Iran, Malaysia, and Nepal tend to demonstrate higher UAD values (generally ranging from 1.0 to 2.7 ton/m^2). This can be indicated by high-density urban environments and a predominance of RC structures [35]. In contrast, European countries (e.g., Spain, Portugal, Denmark, and Norway) show a broader but slightly lower range (0.8–2.3 ton/m^2). Japan reports relatively low values around 0.85–1.11 ton/m^2. On the other hand, UAD averages range from 0.83–0.91 ton/m^2 in the USA. The analysis of UAD generation rates reveals substantial global variability. For instance, the highest recorded value (3.59 ton/m^2) was found in Portugal [38], whereas the lowest (0.58 ton/m^2) was reported for Norway [36]. Turkey's UAD estimates range between 0.94 and 1.37 ton/m^2, aligning closely with the global average. Overall, the collected data suggest that a globally representative average UAD of approximately 1.27 ton/m^2 is reasonable for large-scale modeling or estimating debris generation, acknowledging regional

variability depending on construction typologies and material properties.

After determining the UAD amounts, the total earthquake debris amounts were calculated for the created scenarios. Table 6 presents the amounts of earthquake debris categorized into different scenarios (Table 2) for the earthquake region in Turkey. The anticipated quantities of waste generated by the earthquakes affecting the cities below, calculated under six scenarios designated SC-1 through SC-6, are presented in Table 6. Six scenarios (SC-1 through SC-6) were prepared using two fundamental variables: Unit Gross Area and Unit Area Debris value. Scenarios SC-1, SC-2, and SC-3 all utilize a Unit Gross Area of 120 m^2. Within this specified area, SC-1 implements Approach 1, SC-2 employs Approach 2, and SC-3 utilizes the Average Literature Value. Similarly, scenarios SC-4, SC-5, and SC-6 used the Unit Gross Area of 150 m^2. For this dimension, SC-4 applies Approach 1, SC-5 applies Approach 2, and SC-6 incorporates the Average Literature Value to assess the amount of earthquake waste.

Cities severely affected by earthquakes and total amount were given in bold style

The overall quantities of debris projected to be produced across all the examined cities exhibit a considerable range, fluctuating from an estimated low of approximately 93.9 million tons in the context of scenario SC-1 to a significantly higher estimated total of 159.3 million tons in the context of scenario SC-6, thereby highlighting the considerable variability that is contingent upon the underlying assumptions made and the varying levels of damage severity that were taken into account. The presentation of debris quantities on a provincial basis in Table 6 was to reflect the localized damage distribution relative to the epicenters, as illustrated in Fig. 1. The total debris quantities estimated in this study represent the specific impact of the February 6, 2023, earthquakes and are not based on a generalized 100% collapse assumption. The extrapolation utilized the official count of independent units categorized by the MoEUCC as either 'collapsed' or 'severely damaged and requiring demolition.' This ensures that the results reflect real-world demolition decisions and actual damage intensity. While the absolute tonnage remains event-specific, the derived UAD values provide a generalizable methodology that is critical for pre-disaster planning. These unit-based factors can be utilized in future seismic scenarios to estimate debris generation for building stocks with similar structural characteristics and construction periods.

Among the cities analyzed, Hatay consistently shows the highest waste generation across all scenarios, with projected debris quantities ranging from 37.0 million to 62.8 million tons. At the same time, it is followed in terms of waste generation by Kahramanmaraş, which is estimated to produce between 15.8 million tons and 26.8 million tons, and Malatya, which is projected to generate between 11.9 million tons and 20.1 million tons, and Adıyaman, which is expected to yield a total of between 9.6 million tons and 16.3 million tons of debris. In contrast, Niğde and Kayseri produce the lowest waste quantities, each below 0.5 million tons in all scenarios. The results demonstrate that the majority of the earthquake debris is concentrated in a few heavily impacted provinces—particularly Hatay, Kahramanmaraş, Malatya, and Adıyaman—which together account for the dominant share of the regional total. Overall, the data indicate that the total earthquake-induced construction and demolition waste in the region could range from approximately 94 to 159 million tons, depending on the scenario assumptions. The variance between the scenarios, particularly between field-derived (SC-1, 2, 4, 5) and literature-based (SC-3, 6) estimates, underscores the critical importance of regional data. While the gap between SC-1 and SC-6 reaches 65.37 million tons, a closer inspection reveals that Approaches 1 and 2 exhibit greater convergence, yielding a tighter, more

Table 6 The amount of earthquake debris generated for the cities in the earthquake region (tons)

Cities	SC-1	SC-2	SC-3	SC-4	SC-5	SC-6
Adana	2,248,422	2,402,160	3,050,743	2,810,527	3,002,700	3,813,429
Adıyaman	**9,626,386**	**10,284,600**	**13,061,442**	**12,032,982**	**12,855,750**	**16,326,803**
Diyarbakır	3,082,622	3,293,400	4,182,618	3,853,278	4,116,750	5,228,273
Elazığ	1,984,245	2,119,920	2,692,298	2,480,306	2,649,900	3,365,373
Gaziantep	**6,771,885**	**7,234,920**	**9,188,348**	**8,464,856**	**9,043,650**	**11,485,436**
Hatay	**37,018,763**	**39,549,960**	**50,228,449**	**46,273,453**	**49,437,450**	**62,785,562**
Kahramanmaraş	**15,781,297**	**16,860,360**	**21,412,657**	**19,726,621**	**21,075,450**	**26,765,822**
Kayseri	278,785	297,847	378,266	348,481	372,309	472,832
Kilis	572,383	611,520	776,630	715,478	764,400	970,788
Malatya	**11,874,021**	**12,685,920**	**16,111,118**	**14,842,526**	**15,857,400**	**20,138,898**
Niğde	155,229	165,843	210,621	194,036	207,303	263,275
Osmaniye	2,478,453	2,647,920	3,362,858	3,098,066	3,309,900	4,203,573
Şanlıurfa	2,041,191	2,180,760	2,769,565	2,551,489	2,725,950	3,461,957
Total	**93,913,682**	**100,335,130**	**127,425,615**	**117,392,102**	**125,418,912**	**159,282,018**

realistic estimate of the regional building stock. The results demonstrate that using generic literature values for UAD can lead to substantial overestimation of debris volumes, potentially misguiding logistics and landfill planning. By adopting 120 m^2 and 150 m^2 as representative unit areas for Southeastern Turkey, this study provides a calibrated framework that makes post-disaster waste generation more predictable. Consequently, the presented range supports the need for field-based UAD derivation to achieve more accurate city-scale debris projections. A significant gap is frequently observed between theoretical waste estimates and the actual quantities collected by local municipalities, primarily because structural foundations and underground components are typically left on-site rather than transported to landfills. Literature indicates that the actual volume of waste collected by local governments can be as low as 50–60% of the initial estimates derived from post-disaster surveys [43, 44]. In this study, the discrepancy is addressed by implementing site-specific correction factors that account for on-site backfilling and retained foundations. However, because total debris projections are highly sensitive to these parameters, a ± 5–10% variation in the correction ratios can alter the final regional results by millions of tons. In this study, a sensitivity analysis was conducted by varying the correction factors by ± 10%, confirming that the overall trends in UAD values remained unchanged. While such variations highlight the inherent logistical and operational uncertainties in post-disaster settings, the derived UAD values remain a robust, field-verified baseline for quantifying total structural mass. This uncertainty margin should be considered by waste management authorities when planning for the upper limits of storage and recycling capacities. For instance, Xiao et al. (2023) reported that the amount of demolition waste generated after the earthquakes on February 6, 2023, in Turkey ranges from 450 to 920 million tons. Since they estimated that all affected individuals lived in buildings that were either destroyed or severely damaged, this naturally led to a larger estimate of debris [11]. UNDP's estimates of the earthquakes on February 6, 2023, generated between 116 and 210 million tons of debris, which are closer to this study's results [24]. In addition, Temelli et al. [25] conducted a similar study using UAD values from the literature. They calculated 396 million tons, including the case of demolishing lightly damaged houses. Conversely, SBO and MoEUCC stated that in addition to the collapsed buildings, only risky buildings (severely and moderately damaged buildings) were demolished [20, 21]. The total amount of earthquake waste generated worldwide over the last 50 years was obtained to compare Turkey's current situation regarding earthquake waste generation. The estimated amounts of waste generated by major earthquakes worldwide are summarized in Table 7.

Table 7 Estimated waste quantities resulting from major earthquakes around the world in the last 50 years

Earthquake Location	Year	Magnitude (Mw)	Affected Population (million)	Generated Waste Amount (million)	Reference
Turkey—Kahramanmaraş	2023	7.6–7.7	16.4	93.9–159.3 million ton	**This Study**
				116–200 million ton	[24]
				100–120 million m^3	[20]
				396 million ton	[25]
				450–920 million ton	[11]
Mexico City	2017	7.1	8.4	0.344 million ton	[45]
Nepal-Gorkha	2015	7.8	-	3.23, 13.79 million ton	[6, 46]
Italy-Emilia-Romagna	2012	5.86	-	0.364 million m^3	[47]
Japan- Great East Japan	2011	9.1	-	28 million ton	[48]
New Zeeland-Canterbury	2010	6.1	-	8 million ton	[49]
Haiti	2010	7.0	20	52 million ton	[4]
Italy-L'Aguila	2009	6.3	0.25	2.65 million m^3	[47]
China-Sichuan	2008	7.9	45	20 million ton	[8]
Taiwan Chi-Chi	1999	7.3	-	20 million m^3	[19]
Turkey-Marmara	1999	7.4	25	13 million ton	[4, 50]
Japan-Kobe, Hansin Awaji	1995	7.2	25	15 million ton	[4, 44]
USA-Los Angeles, CA: The Northridge	1994	6.7	0.30	2 million ton	[45]
Italy-Friuli	1976	6.1	-	0.189 million m^3	[47]

The 2023 Kahramanmaraş and Hatay earthquakes in Turkey stand out as the most destructive in terms of waste generation, with estimates ranging from 94–159 million tons (this study) to as high as 450–920 million tons in other reports—far exceeding all other listed events. Despite a magnitude range similar to several past earthquakes (7.6–7.7 Mw), the exceptionally large affected population of 16.4 million contributed to the unprecedented volume of waste. In contrast, earthquakes of comparable or even higher magnitudes produced considerably lower waste. For example, the 2011 Great East Japan earthquake, which registered a magnitude of 9.1 Mw, resulted in the release of 28 million tons of waste. In contrast, the 2008 Sichuan earthquake, with a magnitude of 7.9 Mw, and the 2010 Haiti earthquake, with a magnitude

of 7.0 Mw, generated 20 million tons and 52 million tons of waste, respectively. In contrast, earthquakes of smaller magnitudes, such as the 2017 Mexico City earthquake (7.1 Mw, yielding 0.344 million tons) and the 2012 Italy–Emilia Romagna earthquake (5.86 Mw, producing 0.364 million m^3), resulted in considerably smaller quantities. The Turkey–Marmara (1999) and Japan–Kobe (1995) earthquakes each generated approximately 13–15 million tons of material, consistent with their mid-range magnitudes (7.2–7.4 Mw) and urban impacts. Meanwhile, older or less urbanized events, such as Italy–Friuli 1976 (6.1 Mw, 0.189 million m^3), produced negligible waste volumes in comparison. Overall, the comparison emphasizes that although earthquake magnitude plays a role, population density, construction practices, and urban scale are decisive in determining waste generation. For instance, the 2023 Kahramanmaraş earthquakes represent an extreme case, generating disaster waste amounts several times higher than those of any previously documented events worldwide due to their scale and population affected. On the other hand, population density and the degree of urbanization significantly influence the amount of debris generated by an earthquake. Earthquakes in highly urbanized and densely populated areas generate more waste due to the density of building stock. Similarly, the 1999 Turkey -Marmara earthquake, with a magnitude of 7.4, impacting a population of 25 million, generated 13 million tons of waste [4, 50]. Baycan (2004) stated that around 45 percent of Turkey's population lives in high-risk earthquake-prone areas, mostly in or near urban areas. Thus, the extent of damage caused by the Marmara Earthquake was unfortunately significant [50]. These cases highlight a direct correlation between urban density and debris volume, underscoring the need for robust urban planning and construction practices in earthquake-prone areas.

Limitations

The study focused on RC residential structures, as these represented the predominant damage characteristics and building stock in the affected region. Although efforts were made to ensure representativeness by selecting buildings of diverse ages across three seismic code eras, the sample size was constrained by logistical challenges and safety protocols in the immediate post-disaster environment. While this sample size aligns with similar empirical studies in the literature, a larger dataset could further enhance the precision of future estimations. Several factors may influence the trends observed in this study's results. Safety protocols and recovery operations in the aftermath of the earthquakes necessitated the use of field observations and contractor reports to determine certain structural parameters and correction factors for on-site backfilling. These factors are subject to operational uncertainties because they depend on specific building characteristics and contractors' economic incentives. The regional variations explain the importance of localized strategies in earthquake preparations and debris management. This highlights regions' building codes and construction practices. Policies and regulations tailored to regional building practices, urban density, and resource availability are essential for effective disaster management.

Conclusion

Assessment of earthquake debris amounts is a complex process involving multiple factors. By integrating UAD into debris quantification methods, stakeholders can estimate post-earthquake waste volumes more accurately, facilitating efficient recovery and minimizing environmental impact. In this study, UAD was determined for buildings categorized into three periods: ≤1999, 2000–2010, and 2011–2018. The findings indicate an increasing trend in UAD values for newer constructions, with average values of 0.845, 0.952, and 1.009 tons/m^2 (Approach 1) and 0.933, 0.979, and 1.107 tons/m^2 (Approach 2) for the respective periods. Based on these figures, maximum debris quantities for the most affected cities were estimated at approximately 63 million tons in Hatay, 27 million tons in Kahramanmaraş, 20 million tons in Malatya, and 16 million tons in Adıyaman. Depending on the scenario, the total earthquake debris generated in the affected region is estimated to range from 93.9 to 159.3 million tons, underscoring the substantial scale of debris management required after the disaster.

However, it is important to emphasize that these UAD values are derived from severely damaged RC residential buildings subjected to a high-magnitude earthquake. Therefore, the results are most applicable to similar structural systems and damage scenarios, rather than being universally transferable to all seismic contexts. While the findings offer valuable insights for regions with construction standards similar to those in Turkey, they should be applied with caution to different building typologies or to lower-magnitude events. This study provides a critical baseline for disaster waste management, highlighting the roles of building age and evolving construction standards in debris generation. The integration of theoretical material-stock estimation with empirical field data remains critical to validating UAD coefficients. Moving forward, developing a comprehensive Material Flow Analysis (MFA) framework is recommended. By comparing theoretical material weights with real-time weighbridge data and landfill volume dimensions, future research can establish high-quality debris coefficients. Such

validated data will be pre-disaster recovery acts tailored to the structural characteristics of the Turkish building stock.

Future research should consider these findings to enhance debris estimation models. One of the key directions involves the transition from deterministic approaches to probabilistic debris modeling, which would better account for the inherent uncertainties in structural damage and post-disaster logistics. Furthermore, future studies should focus on integrating UAD values into seismic scenario analysis to enable more dynamic waste estimation based on specific ground-motion intensities and the spatial variability of damage. There is also a critical need to develop standardized debris intensity coefficients for structural typologies beyond residential buildings, incorporating different occupancy types and construction materials. Finally, investigating the influence of innovative construction techniques on UAD will provide actionable data to optimize building codes to minimize earthquake debris generation at the source. Expanding datasets across diverse geographic areas remains essential for validating these standardized coefficients at both local and global scales.

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Declarations

Competing interests The authors declare that there is no conflict of interest.

Generative AI technologies in the manuscript preparation process During the preparation of this work, the authors used ChatGPT and Gemini in order to enhance the clarity and fluency of selected passages. After using these tools, the authors reviewed and edited the article as needed.

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Authors and Affiliations

Kadir Özçelik[1] · Ali Tamer Çetinkaya[1] · Kadriye Elif Maçin[1] · Hüseyin Güven[1] · Mahmut Altınbaş[1] · Mehmet Zeki Duman[2] · Osman Atilla Arıkan[1]

✉ Kadir Özçelik
ozcelikk@itu.edu.tr

[1] Department of Environmental Engineering, Istanbul Technical University, Istanbul 34469, Turkey

[2] Malatya Metropolitan Municipality, Malatya, Yesilyurt 44080, Turkey