

5. DAMAGE TO BUILDINGS AND DWELLINGS

The main types of building materials in Peru are reinforced concrete, masonry, and adobe/tapial. Reinforced concrete is used for public and relatively few residential buildings, mainly in urban areas. On the other hand, more than 80% of the housing infrastructures are made of masonry and adobe/tapial while in rural areas almost 70% of the dwellings are made of the latter [INEI, 1993]. These structures suffered partial and complete collapse in cities like Moquegua. Although completely collapsed reinforced concrete and masonry structures were not observed during the survey, several of them suffered extensive damage and required demolition and reconstruction.

5.1 SEISMIC DESIGN CODE

In 1997, the current Seismic Design Code was enacted. The Code establishes procedures for the static and dynamic analysis of structures and its use is mandatory. In spite of this, a large percentage of the structures, especially dwellings, do not comply with its requirements.

According to the Code [SENCICO 1997], the seismic amplification factor is evaluated as:

$$C = 2.5 \left(\frac{T_p}{T} \right)^{1.25} \leq 2.5 \quad (5.1)$$

where T_p = period that establishes the limit of the spectra plateau for each type of soil and T = structure's fundamental period. This coefficient represents the amplification of the structure response with respect to the ground motion. The code classifies the soils into several groups according to their mechanical properties, layer thickness, fundamental period of vibration and shear wave velocity, and different T_p is given to each group of soil. As for exceptional soil types, the code requires a more comprehensive study and recommendations from geotechnical experts. Formulas are also given for the calculation of the structure fundamental period.

In a static analysis, Equation (5.2) provides the base shear force, whereas in a dynamic case, the acceleration spectrum is given by Equation (5.3)

$$V = \frac{ZUSC}{R} P \quad (5.2)$$

$$S_a = \frac{ZUSC}{R} g \quad (5.3)$$

where, Z = zone factor ranging from 0.15 to 0.40, U = use factor that falls between 1.0 to 1.5, S = soil factor ($1.0 \ll 1.4$), R = reduction factor ($5.25 < < 10$), P = structure's weight, and g = gravitational acceleration.

The code classifies buildings according to their importance, structural system, and layout regularity, and describes appropriate types of structures to be used for specific purposes. It also describes specifically the displacement limitations, minimum requirements for joint thickness, procedures for modal superposition analyses, designs of non-structural members, etc.

In general, the Peruvian Seismic Design Code covers all the necessary aspects of design, and is mandatory. Each time of construction, it is a must for a licensed contractor to submit a set of design drawings for revision and approval. The design is then reviewed by a group of experts and changes are put if necessary. It is, however, often reported that buildings do not fulfill its requirements probably because in-situ inspections are not mandatory. Moreover, many people, without being licensed, have been constructing their dwellings.

5.2 STRUCTURAL DAMAGE SURVEY

The JSCE reconnaissance team surveyed damage to structures at Tacna, Moquegua and Arequipa. The summary of its findings is presented hereinafter.

RC structures

Damage to RC structures can be categorized as follows:

(1) Damage to short columns: This type of damage was extensive at schools and public buildings. Insufficient gaps between columns and non-structural elements caused large shear forces to be induced on the short columns (**Photos 5.2 and 5.3**). The damage was the worse for the insufficient transverse reinforcement and for the rusty rebars causing spalling of cover concrete.



Photo 5.2 (above) Municipality office, Tacna



Photo 5.3 (right) Andres Avelino Caceres School, Tacna. The green sign “S” on the column says that the place is “safe” during a seismic event.

(2) Damage to columns for elevated water tanks: In the photos below, damage was found localized at both the columns-tank connections and the short columns.



Photo 5.4 Elevated water tank, San Antonio School, Tacna



Photo 5.5 Elevated water tank at a residential building, Tacna



Photo 5.6 Elevated water tank at a residential building, Tacna.

(3) Deficiencies in structural layout: The current code encourages the use of stiff frames in both longitudinal and transversal directions of a building. It is, however, a customary of long standing to provide them only in one direction, and it does not seem to be done away with ease (See **Photos 5.7** and **5.8**).

(4) Deficiencies in placement of utility pipes, insufficient concrete cover in structural elements, and finishing falling (Photo. 5.9)



Photo 5.7. In the first floor, deep beams are provided in one direction only whereas in the second floor they are provided in both directions.



Photo 5.8. Detail of the first floor of building in **Photo 5.7**.



Photo 5.9. Detail of concrete cover spalling due to insufficient cover and utility pipe in the column border.

(5) Pounding: An insufficient joint opening between two buildings caused pounding (**Photo 5.10**).



Photo 5.10. Pounding between two buildings at Andres Avelino Caceres School, Tacna.

Schmidt hammer tests were carried out at Mariscal Ramón Cáceres School in Tacna, San Antonio School in Moquegua, and the Civil Engineering Faculty Building at the UMSA in Arequipa. Concrete strengths were all above 280kg/cm² excluding the one (150kg/cm²) measured at the building of the Mariscal Ramón Cáceres School constructed by FONCODES.

In general, most of the failures reported herein could have been avoided with a better construction practice. This shows the importance of a supervising system not only at the design but also at the construction stages.

Masonry structures

Reinforced masonry structures appropriately designed and constructed performed well under the seismic loads. However, unreinforced masonry and poorly constructed buildings sustained in-plane and out-of-plane failures.



Photo 5.11. Out-of-plane failure in an unreinforced masonry dwelling



Photo 5.11. In-plane failure of a masonry infill.

Hollow bricks with horizontal perforations were often used in dwellings constructed by their owners though the Masonry Design Code (CAPECO, 1997) forbids it.

Photo 5.13 shows that flexible joints between masonry infill walls and RC frames successfully minimized the damage. Only fragments of thick mortar finishing came off.



Photo 5.13. Masonry infill parapet at San Antonio School, Moquegua.

Adobe structures

In general, adobe structures performed badly as observed in many other earthquakes. **Figure 5.1** and **Photos 5.14 to 5.18** present collapsed adobe structures neighboring reinforced masonry structures, which suffered only minor damage.

Recently, Zegarra et al (2000) proposed a technique for strengthening of existing adobe structures by providing welded wire reinforcement mesh to the adobe walls. As part of the study, 19 adobe houses at different locations in Peru were reinforced. The dwellings located in the areas struck by the Atico Earthquake reportedly performed well and served as shelter for the residents of the surrounding unreinforced adobe houses, which collapsed.

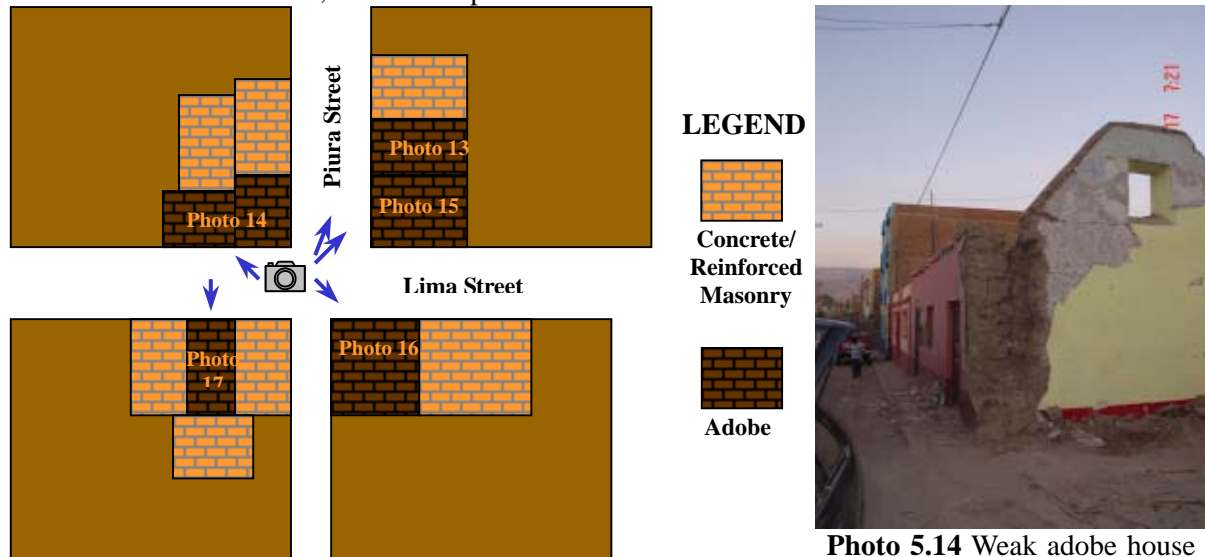


Figure 5.1 Location of the photos 5.14 to 18



Photo 5.14 Weak adobe house corner



Photo 5.15



Photo 5.16



Photo 5.17



Photo 5.18

5.3 DAMAGE ASSESSMENT THROUGH MICROTREMOR MEASUREMENTS

Microtremors were used to identify predominant periods of damage and undamaged structures. At Moquegua, measurements were done at San Antonio School. Three buildings (**Photos 5.19** and **5.20**) whose characteristics are presented in **Table 5.1** were surveyed.

Table 5.1. Characteristics of the San Antonio School surveyed buildings

ID	Building	Number of stories	Remarks
A	Laboratory and teacher’s room	2	Minor damage
B	High school classrooms	2	Damage to non-structural elements. Thick plaster fell from the masonry walls. Some concrete spalling due to short column effect.
C	Building in front of High school classrooms	1	No damage at all



Photo 5.19. Typical 2-story building



Photo 5.20. 1-story building

Microtremors were measured simultaneously on the ground and on top of the 1st story slab. The Fourier Spectra of both recordings was divided to identify the structure predominant period along two principal directions. The transfer functions obtained in this way are presented in **Figures 5.2 to 5.4**.

The transfer functions of Buildings A and B show one peak in the X direction and two peaks in the Y direction, each peak corresponding to one vibration mode. The shift of the predominant periods towards larger values observed in Building B with respect to Building A reflects the damage undergone by the former structure. For instance, the larger period observed in Building A (Y direction) is 0.3sec, which is smaller than the 0.45sec observed for Building B.

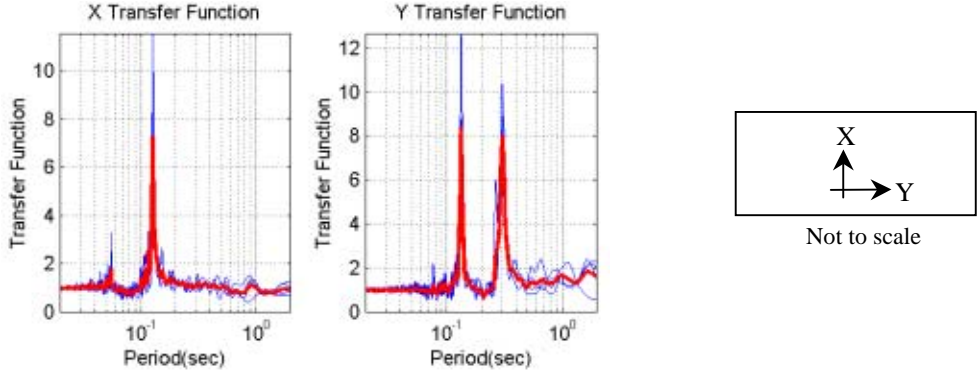


Figure 5.2. Building A transfer function and X and Y axis direction

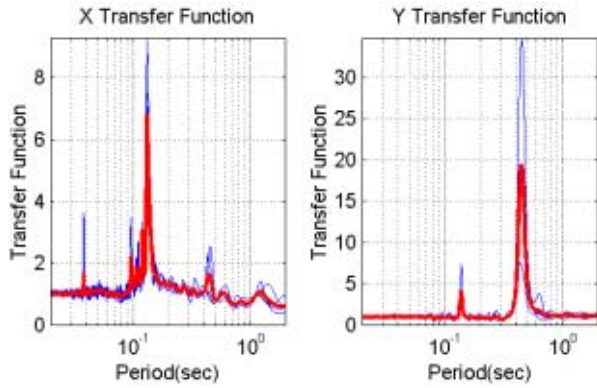


Figure 5.3. Building B transfer function

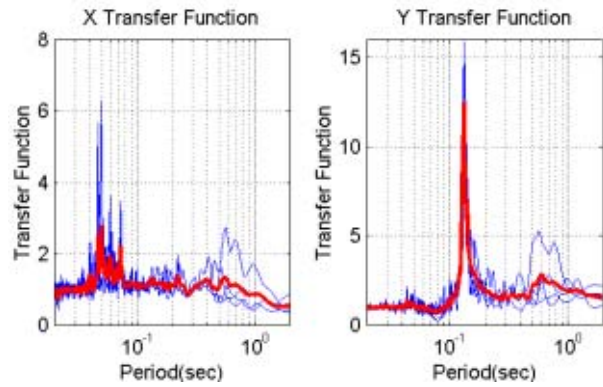


Figure 5.4. Building C transfer function

Building C predominant periods are 0.05 and 0.12sec in the X and Y directions, respectively. These values are smaller than the correspondent values for Buildings A and B due to the difference in the number of stories. Building C is stiffer in the X direction, in which masonry walls are provided to resist shear, than in the Y direction, in which the structures is mainly a RC frame.

Microtremors were measured at several other buildings. Appendix A in Chapter 2 presents a detailed list of the measurements, which are available upon request to the JSCE (<http://www.jsce.go.jp>).

5.4 THERMAL POWER PLANT IN ILO

Construction of thermal power plants

The construction of Ilo thermal power plant started in June 1998, and the trial operation of the plant began in May 2000. The plant has started its business operation since October 2000. The electricity generated by this plant has been supplied to the Southern Peru Copper Corporation (SPCC), and recently a small part of electricity is supplied also to Ilo and other cities for public use. The plant is located 25 kilometer south of the central area of ILO city. A Japanese multinational, Hitachi Corporation Ltd., made a full-turnkey contract on this plant with a Peruvian corporation, Energia Del Sur, which is fully owned by a Belgian company, Tractbell. All the related facilities as well as the equipment for generating electricity, such as turbine, generator, and boiler, have been constructed under the management of Hitachi Corporation. Supplies from over 235 companies originating from 24 oversea countries, were well organized and synthesized into the construction project within a short period of 30 months.

This plant is located on a terrace of about 25 m above sea level facing a very shallow tidal land extending deep inland from the shore. For this reason, a 1.3 km-long pier was constructed to connect the plant with a platform for unloading coals from 71,000 DWT ships. A semi-siphoned piping system was constructed along the pier to obtain seawater. A multi-loop vapor-pressing type desalting system transforms seawater into freshwater for the entire use in the plant. The specifications for the main equipment are summarized in **Table 5.2.1**, and **Photos 5.2.1** and **5.2.2** are complete views of the power plant. **Figures 5.2.1** and **5.2.2** illustrate an outline of the earthquake-inflicted damage observed in this power plant.

Table 5.2.1 Specifications of main equipment in the plant (After Katayose, 2000)

Equipment	Specification
Turbine	TCDF-26, 16.67 MPa(A) 538/538degree C, 3600 rpm
Electric Generator	Whole-closed air-cooling, brush-less, AC Exciter 169 MVA, 17 kV, 60 Hz, 0.8 PF
Boiler	Drum-type, natural circulation Coal fired (Light oil in case of starting or emergency) MCR: 432 t/h, 17.36 MPa(A) 541/541degree C
Chimney	130 meter high
Coal delivery	Un-loader (2x 750 t/hour) Stacker (1x 1500 t/hour) Reclaimer (2x 225 t/hour) Stock capacity 200,000 t
Desalting system	Multi-loop vapor-pressing type 2x 1,300 t/day
Water circulation	15,700 m ³ /hour x 33.5m Pump 1850 kW
Main transformer	169 MVA(ODAF) HV: 220 kV-OLTC LV: 17 kV, %Z=13%
Circuiting place	220 kV GIS, 6 Bay
Control system	Unit/Common DCIS Turbine controller, PLC, CRT operation



Photo 5.2.1 View of the power plant



Photo 5.2.2 View of the power plant

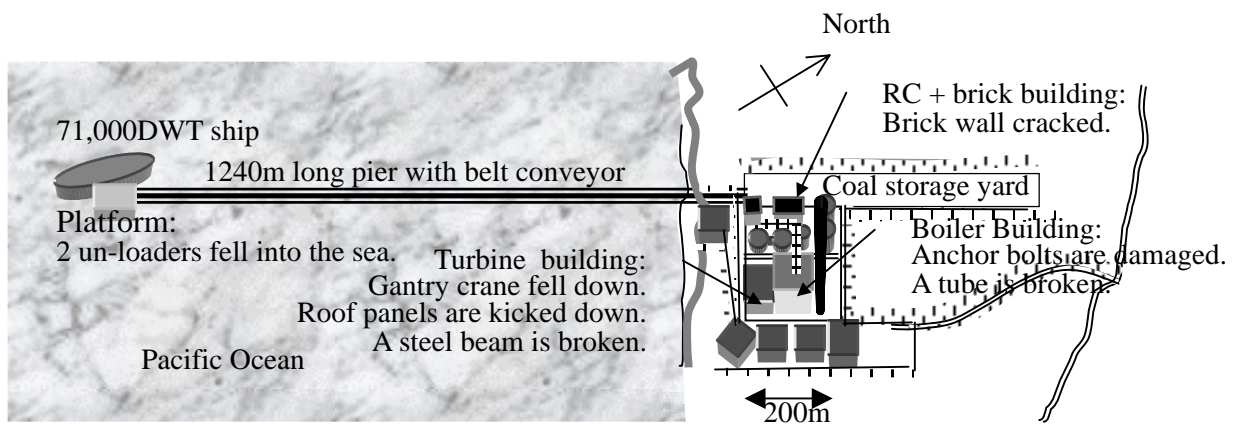


Figure 5.2.1 Earthquake Damage of Ilo 125MW Thermal Power Plant, Plan

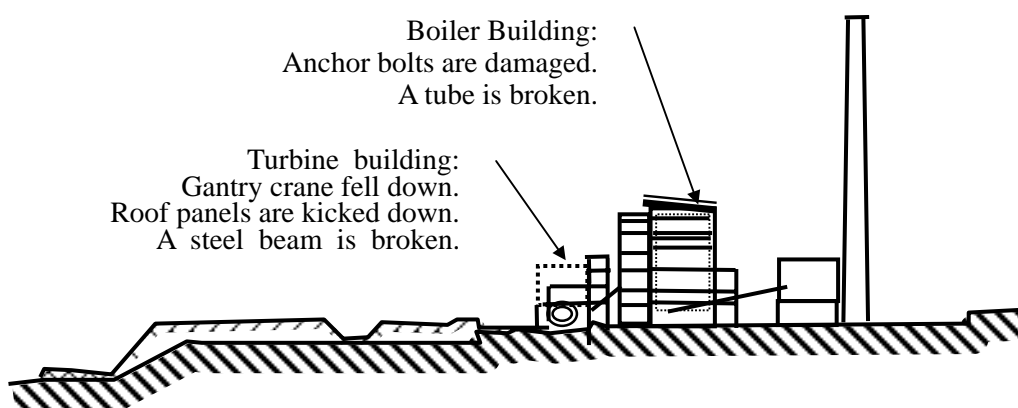


Figure 5.2.2 Earthquake Damage of Ilo 125MW Thermal Power Plant, Elevation

Damage to column anchorage in boiler plant

Photo 5.2.3 shows the boiler plant built in a multi-story steel braced frame. Since the detail dimensions of the frame were not available to the author, the elevation of a similar boiler plant (Radiant Boiler Type C , 125MW Shin-Ebetsu Power Station, Hokkaido Electric Power Ltd.) is shown in **Figure 5.2.3** for the readers information. **Photos 5.2.4** through **5.2.7** show the damage to column anchorages in the boiler plant frame. Some of the column anchorages connected to the steel brace members were damaged.



Photo 5.2.3 A view of boiler plant

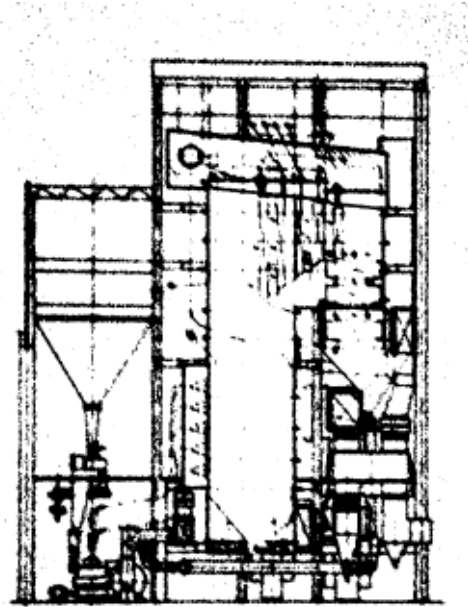


Figure 5.2.3 A framing elevation of similar boiler plant in Japan (Shin-Ebetsu Power Station)



Photo 5.2.4 Damaged column anchorage



Photo 5.2.5 Yielding of anchor bolts in 8-bolt layout column base



Photo 5.2.6 Almost no damage is seen at interior column anchorage, 12-bolt layout



Photo 5.2.7 Completely broken anchor bolts in 4-bolt layout column anchorage

Photo 5.2.4 shows the end of an exterior column connected to the vertical brace of a H-shaped cross-section with cover plates. This column end was anchored to its base concrete with 8 bolts, and all the bolts yielded at their threaded portions, and pulled as much as 2 cm up as shown in **Photo 5.2.5**. The next interior column end had 12 anchor bolts and they did not suffer any serious damage as shown in **Photo 5.2.6**. One column end had only 4 bolts, and they were all completely broken as shown in **Photo 5.2.7**. In all these cases, vertical braces were not damaged at all. This implies that these anchor bolts might be proportioned in reference to a certain working stress under a specified design load, and apparently, capacity criteria to assure brace yielding was not adopted. Yielding of exterior anchor bolts caused redistribution of design traction forces, and resulted in breaking of anchor bolts in other column bases. Structural damage to this extent can be ranked as slight to moderate, but unluckily, a tube was reportedly damaged and steam was rising during the earthquake. A long inspection time is usually necessary for a damaged pipe system to be fully restored, causing some serious delay in resuming normal service.

Crane falling into turbine room

In the turbine building next to the boiler plant, a gantry crane fell down on the roof of the turbine room as shown in **Photos 5.2.8** through **5.2.12**. This crane was used for maintaining the turbine room, and for this reason, the roof panels were removable. The crane pushed down the roof panel into the turbine room. The guide rail for gantry crane was connected to its girder by clips and fastening bolts. As shown in **Photo 5.2.11**, these fasteners were all broken and missing, and this caused the crane to fall. The impact load on the roof panel must have been large enough for the steel sub-beam of the roof panel to be severely damaged. The shear connections at its both ends were also sheared off as shown in **Photo 5.2.12**. The roof panel hit a pipe in the turbine room and damaged it slightly. However, this earthquake did not do any serious damage to the main structure (steel braced frame) of turbine building.

Other damage in the plant

As shown in **Figure 5.2.1**, two un-loaders (bucket-type) at the platform fell down into the sea. Also the plant administration office building, a RC frame with brick infill, was slightly damaged.



Photo 5.2.8 Gantry crane fell down



Photo 5.2.9 Crane were used for maintenance of turbine room



Photo 5.2.10 Crane kicked down the removable roof panels



Photo 5.2.11 Fasteners that fixed crane rail were completely broken



Photo 5.2.12 Steel sub-beam supporting roof panels was completely broken

5.5 SUMMARY

In the Atico earthquake, total 41,394 dwellings were reportedly destroyed or heavily damaged. In urban areas, more than 80% of the housing infrastructures are made of masonry and adobe/tapial while in rural areas almost 70% of the dwellings are made of the latter [INEI, 1993]. As for RC buildings, the Peruvian Seismic Design Code covers all necessary aspects of their designs, and it is mandatory for a licensed contractor to submit a set of design drawings for revision and approval. It is, however, often reported that buildings do not fulfill its requirements probably because in-situ inspections are not mandatory. Moreover, many people, without being licensed, have been constructing their dwellings, and damaged RC structures are mostly found in them. They are grouped into the following 5 categories: (1) cracked short columns, (2) cracked supports for water tanks, those caused by (3) deficiencies in structural layouts, and (4) placement of utility pipes, insufficient concrete cover in structural elements, and finishing falling, and those caused by (5) poundings.

In general, adobe structures performed badly as observed in many other earthquakes except those with welded wire reinforcement meshes provided to their walls.

Ilo thermal power plant suffered some damage to its RC frames for the boiler plant and to its gantry crane, the latter broke through the roof of the turbine room.

(5.1, 5.2, 5.3/ Kimiro MEGURO, Paola MAYORCA, Jörgen JOHANSSON, IIS, Univ., Tokyo)
(5.4/ Kenichi OHI & Ruben GUZMAN, IIS, University of Tokyo)
(5.5/ Kazuo KONAGAI, IIS, University of Tokyo)

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