 doi:10.20944/preprints201807.0441.v1

Article

A feasibility review of innovative prefabricated footing systems for residential structures

Bertrand Teodosio [1,] *, Shanaka Kristombu Baduge [1], Tuan Duc Ngo [1], Priyan Mendis [1], Maral Tecer [2], and David Heath [1]

[1] The University of Melbourne, Centre for Advanced Manufacturing of Prefabricated Houses; bteodosio@student.unimelb.edu.au
[2] The Australian Reinforcing Company; maral.tecer@arcreo.com.au
* Correspondence: bteodosio@student.unimelb.edu.au; Tel.: +61-410-517-555

Abstract: The consistently positive Australian economic environment and stable population increase have led to a higher demand for new houses in recent years. Prefabrication is a promising method to help alleviate the issues related to housing shortage and affordability due to reduced material wastage, construction delays due to weather conditions, unexpected costs, shortage in labour and onsite risks. With the advancements in automation and manufacturing methods such as Design for Manufacturing and Assembly (DfMA), the quality and precision of prefabricated materials is tightly controlled, and the fabrication and assembly period are reduced. However, the full potential of prefabricated construction is yet to be realised in part due to most of developments being focused on its superstructure. A review of the current available options suitable for houses is necessary to understand the present state of the residential footing industry, which will help evaluate the necessary innovations for the growth of the Australian construction industry considering the local reactive soil conditions. This paper presents a summary of existing footing systems and potential prefabricated footing solutions for low-rise residential structures with one storey to two storeys. This paper also reviews the benefits and challenges of designing, manufacturing, transporting, handling and installing of prefabricated footings on site, which have great influence on the acceptance of these innovative footing systems.

Keywords: prefabricated footing system; residential structures; reactive soils; modular construction; design for manufacture and assembly

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1. Introduction

The positive Australian economic environment and population increase have led to a growing demand for residential structures. The Australian property market for dwellings has seen consistent increases of approximately 3% per annum since 1970s [1]. The average total number of dwelling commencements from 2001 to present is on average 150,000 per year [2] and yet, the cumulative housing shortage is still around 220,000 [3]. This strong demand for houses and acceptable rate of dwelling completion has been countered by a shortage of skilled trades which has constrained sustainable growth in the housing industry [4]. In turn, there have been price increases, material and labour shortages, issues related to construction quality and delays [5]. Prefabricated housing offers a solution for these challenges by building houses with less waste, greater certainty for building costs, improved site safety, controlled quality of materials and workmanship, and shorter construction cycle time [6]. Furthermore, prefabrication only requires in-situ assembly reducing the necessity for skilled trades for site preparation, general building, bricklaying, carpentry, ceramic tiling, joinery, plastering, other trades [7].

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Prefabrication, the method of constructing off-site then transporting and assembling on-site, has been adopted for the superstructure of residential houses for many years [5]. Significant advances in the design and construction of superstructures have increased the number of prefabricated houses built in countries like Japan and the United States of America [8,9]. Safety of prefabricated elements has also been globally investigated to assure the robustness of superstructures [10]. However, most innovations are focused on the superstructure of houses, accepting conventional methods for construction of the footing [11]. Constructing footing systems using traditional cast-in-place concrete causes site disturbance and requires more construction, which lead to environmental degradation and construction delays [12].

The prefabrication of footing systems has the potential to have a positive impact on the housing industry by: improving construction quality, improving sustainability, reducing construction delays, reducing the industry's reliance on skilled labour, and increasing certainty in project expenses [13]. To date there has been minimal development of light-weight prefabricated footing solutions that are suitable for low-rise residential structures, which will aid in solving the housing shortage and reduce the dependence on skilled labour.

Because of the collapse of automotive industry in Australia due to closure of motor vehicle manufacturing plants, employees with automation and manufacturing expertise transit to construction industry. It increases interests for automation and prefabrication in construction industry while creating more job opportunities to retrenched employees of automotive industry. Therefore, prefabricated foundation system can cater growing residential construction industry while creating more job opportunities and smooth transition for retrenched employees who have expertise and skills in automation and manufacturing.

A review of prefabricated footing systems currently available in the market is necessary to understand the present state of the footing industry for residential structures considering reactive soil conditions. Results from this review will help to identify possible innovations that may be accepted not only in the Australian housing industry but also for residential construction worldwide. The aim of this paper is to present an overview of existing footing systems and potential prefabricated solutions considered suitable for low-rise conventional and prefabricated residential structures. This paper also aims to identify the benefits and challenges of designing, manufacturing, handling, transporting and installing innovative prefabricated footings on site, which are informative and beneficial to aid on market acceptance of prefabricated footing solutions for residential projects.

2. Current footing systems

Traditional and innovative footing systems being used in practice for both conventional and prefabricated houses classified as Class 1 and Class 10a [14] are presented in this section. This section is divided into shallow footing systems and deep footing systems. A system is considered a shallow footing if the depth-to-width ratio is less than 5.0 and the system transfers applied structure loads near to the surface. On the other hand, a system is considered a deep footing if the depth-to-width ratio is equal to or greater than 5.0 and the system transfers applied structure loads to a deeper and stronger subsurface layer.

2.1. Shallow footing systems

Shallow footings are commonly used for houses. The Australian Standard 2870: residential slabs and footings [15] sets out the criteria for site classification for reactive soils and the design and construction of footing systems used in Australian residential structures. The shallow footings being used in practice for houses are: stiffened raft, footing slab, waffle pods, stiffened slab with deep edge beams and strip footings. The site class (Table 1) is assigned base on the characteristic surface movement (y_S) due to expansion and shrink of reactive clayey soils, calculated using

$$y_S = \frac{1}{100}\sum_{n=1}^{N}(I_{pt}\overline{\Delta u}\,h)_n = \frac{1}{100}\sum_{n=1}^{N}(\alpha I_{ps}\overline{\Delta u}\,h)_{n}, \quad (1)$$

where I_{pt} is the instability index (pF), Δu is the average soil suction change over the layer thickness (pF), α is the lateral restraint factor, I_{ps} is the soil shrinkage index (%/pF), h is the layer thickness, and N is the number of soil layers. The specification of a suitable footing (depth of the beams and internal ribs, size and amount of reinforcement) depends on the classification of sites and the nature of the superstructure (e.g. full masonry, articulated masonry, brick veneer, cladding, weatherboard, etc.). For expected surface characteristic movement and for given wall system, differential settlement is limited selecting adequate stiffness to the foundation so that superstructure within permissible damage levels. The stiffness for the foundation is provided by slab raft or series of stiffening beams or internal rib beams.

Table 1. Site classification based on surface characteristic movement (y_S) [15].

Site class	Foundation	y_S (mm)
A	rock and sand	0
S	slightly reactive silt and clay	0-20
M	moderately reactive silt and clay	20-40
H1	highly reactive clay	40-60
H2	very highly reactive clay	60-75
E	extremely reactive clay	>75
P	filled, soft silt or clay, loose sands, sandslip, mine subsidence, collapsing	varying

Different shallow footing systems adopted in low-rise housing, from traditional to innovative, are presented in this section. The different types of footing systems include: stiffened rafts, block piers or pad footings with ground anchors, footing systems with bracing, footing systems with beam clamps, corrugated panel cover with poured concrete, footing systems with a deadman, an semi-adjustable column stands with tension anchors, waffle pod raft and permanent on-ground formwork. These have depth-to-width ratios less than 5.0 and transfer applied structure loads near to the ground surface.

2.1.1. Stiffened rafts

One of the most commonly used footing system is the stiffened raft, comprised of reinforced concrete beams and slabs across the entire floor plan (Figure 1). Excavation is necessary, which is dependent on the depth of the beam and its slab thickness. Formwork is then installed, and concrete is poured in-situ, which shapes the profile of the stiffened raft system. The slab is usually raised above the ground level to ensure that stormwater will not flow into the house and cause damage. The stiffened raft requires significant site preparation including grading, excavation, formwork setup and concrete curing.

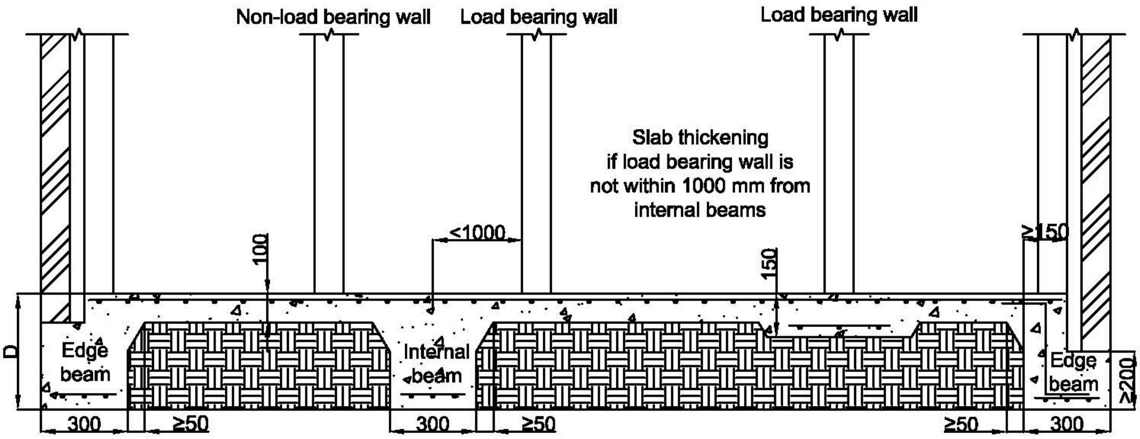

Figure 1. A typical stiffened raft design adapted from [15].

2.1.2. Piers, pads and ground anchors

Another type of shallow footing is a system with block masonry piers or pads with ground anchors [16]. Stacked block piers can be a single block pier or a double block pier (Fig. 4). On the other hand, the pads can be a double pad or a triple pad. The block piers or pads are installed under the main beams of prefabricated houses. The typical block pier or pad height ranges from 0.9 m to 2 m off the ground and spaced from 1.5 m to 3.0 m apart depending on the house design and soil type. The ground anchors are attached to the beams of prefabricated houses using steel straps to resist wind uplift forces. This footing system is adaptable to local site conditions and does not require a strict dimensional manufacturing and installation tolerance. Perimeter walls made up of stacked blocks may also be a part of the footing system. A reinforced version of the block piers is also available holding up chassis that supports prefabricated houses in the United States of America [17]. This chassis beam is similar to the footing system of [18], however, instead of using a reinforced pier, pads supporting the chassis beams are used. The chassis beams are ideal due to its light weight and easy assembly. However, the performance of the system for reactive soil has not been tested yet. This footing system has an advantage when installed on reactive soils since the contact between the footing system and the reactive soil minimised. However, the pads should have supplementary ground supports (i.e. ground anchors, reticulated piles or screw piles).

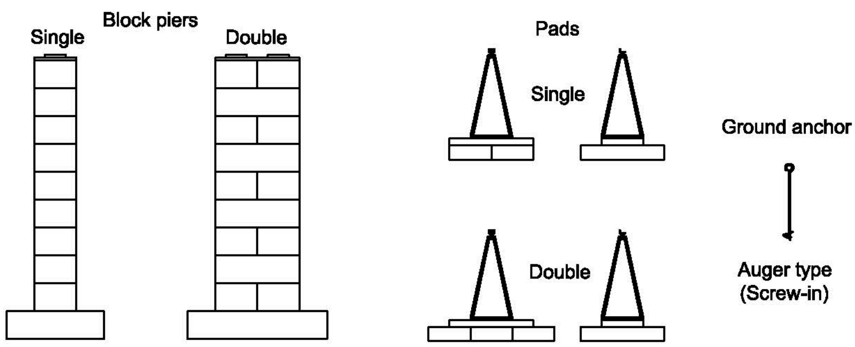

Figure 2. Footing systems using single or double block piers or pads with ground anchors.

2.1.3. Braced masonry piers with metal straps

Another footing system includes braced masonry piers on cast-in-place concrete pads with metal straps (Figure 3) that are utilised to resist vertical and lateral loads such as extreme wind conditions and earthquakes. The metal straps are integrated in the footing system redistributing the loads to adjacent portions of the footing system. However, if straps are loaded to their maximum capacity,

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redistribution of load may lead to progressive failure and collapse. To prevent progressive failure, redundant straps are necessary but may be inefficiently designed.

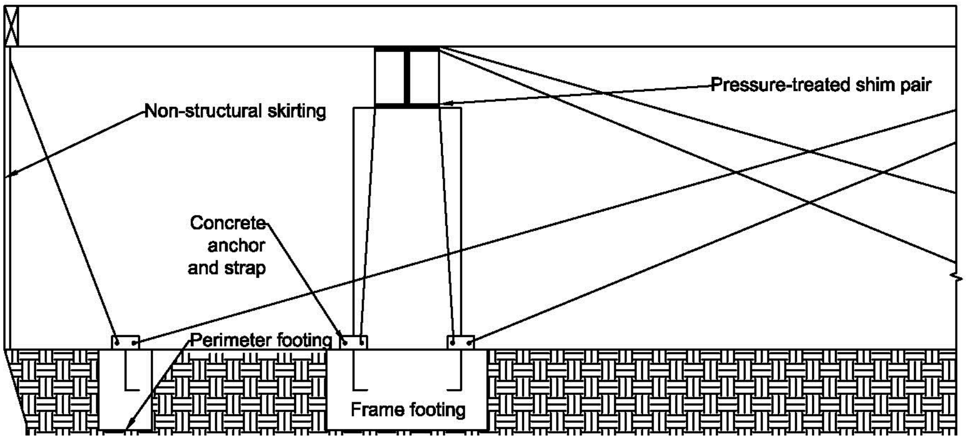

Figure 3. A footing system with bracing using metal straps.

2.1.4. Piers and beam clamps attached to I-beams

Alternatively, a footing system comprised of a galvanised steel pan having a 3-bolt connected tubes (Figure 4) can be used. The V-shaped component has tubes connected with the pan by carriage bolts known as a beam clamp. The other ends of the tubes are then attached to the flanges of I-beams using connectors. The mechanism relates to the tension and compression load distribution from the base pad at one pier to the I-beams. These footing systems can also be used for retrofitting existing substructures.

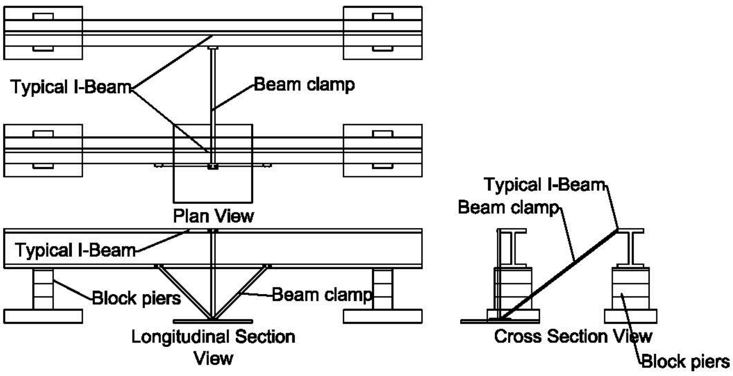

Figure 4. A footing system with an I-beam and a beam clamp.

2.1.5. Structural panels as perimeter wall support

Another hybrid footing system is comprised of structural panels attached around the perimeter of houses with pour-in concrete (Figure 5). Concrete is cast into the structural panels that will act as a perimeter wall support. However, block piers with beam supports are still necessary under the middle area of a prefabricated house.

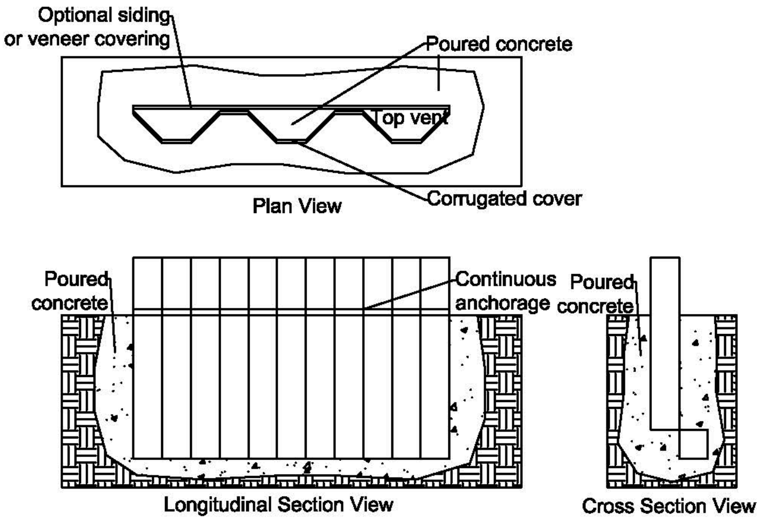

Figure 5. A footing system with structural panels and cast-in-place concrete.

2.1.6. Structural panels as perimeter wall support

An alternative option is a footing system made up of several components including a pivoting deadman (Figure 6). It is applicable to most types of soil except gravelly sands with little or no fines, since these soils does not have the cohesion the deadman mechanism requires. Houses are connected by a telescoping arm consisting of a locking frame clamp that transfers both tension and compression loads to the pivoting deadman.

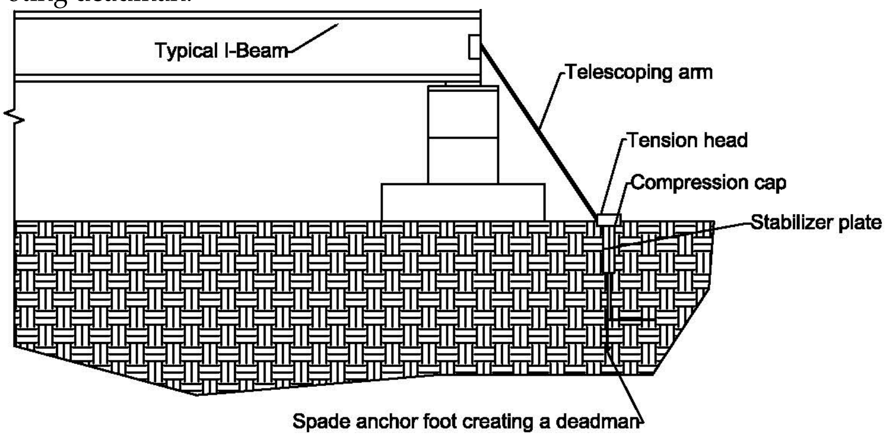

Figure 6. A footing system with telescoping arm and a spade anchor deadman.

2.1.7. Semi-adjustable column

Another footing system is made up of a permanent support column that replaces blocks and anchors of houses (Figure 7). It is designed to be fastened to I-beam flanges that has an adjustable cap plate that can be positioned to a desired elevation. However, once the installation is finished, the height cannot be adjusted since the rotation of the cap plate is restricted. The forces are transferred by the footing system to the cast-in-place concrete pad, typically the surface of an isolated or a strip footing. This system has the advantage of adjusting the slab in case of differential settlement due to soil swell and shrink, differential loading conditions, uneven ground conditions and earthquakes. Also, prefabricated volumetric modules of superstructure can sit on the stumps and connected to the substructure.

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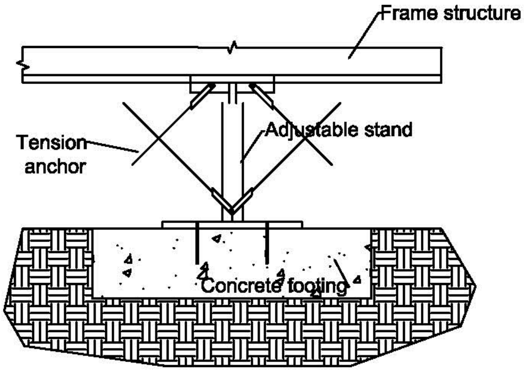

Figure 7. A permanent support column system embedded in a concrete footing with tension anchors.

2.1.8. Waffle pod rafts

On-ground footings are commonly designed with permanent moulds. One of the commonly used integrated formwork footing system is the waffle pod (Figure 8). Other types of on-ground footings include post-tensioned waffle pods [19], or different shapes, materials and dimensions of modular cardboard, Expanded Polystyrene (EPS), polypropylene (PP) or polyethylene (PE) formwork [20].

The most common on-ground footing system in Australia for low-rise residential structure is the waffle pod raft. It is comprised of closely spaced beams and voids created by formed voids (e.g. EPS, PP, PE, card board). The spacing of internal beams is approximately 1.1 m centre-to-centre with an internal beam width equal to 110 mm. The internal and edge beams vary depending on the house wall system (i.e. clad frame, articulated masonry veneer, masonry veneer, articulated full masonry and full masonry) and its site classification (Class A, S M, H1, H2 and E). A minimum of 300 mm wide edge beams are required for full masonry and masonry veneer systems where 110 mm wide edge beams are required for cladding frames and articulated masonry veneer. The internal and edge beam depths range from 300 mm to 1100 mm as specified in AS 2870. Beam excavation is not necessary, and the slab thickness of waffle pods is typically thinner (85 mm) than raft slabs (100 mm). Waffle pods shall be laid out on a levelled surface; hence, they are only used in sites that do not have significant slopes (e.g. sites requiring cut and fill). In addition, since the whole footing system is resting on the ground without anchors, it is not advisable to adopt these systems in areas with high cyclonic winds due to the limited resistance to uplift forces.

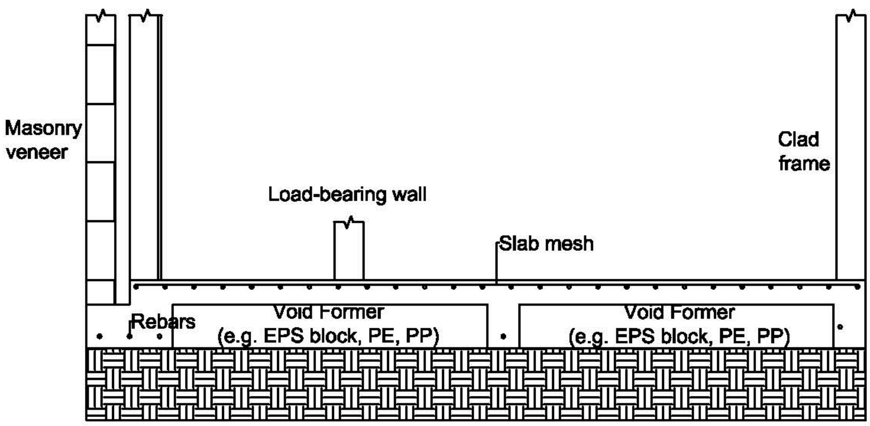

Figure 8. A typical waffle pod system adapted from AS 2870-2011 [15].

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2.1.9. On-ground permanent formwork systems

Many on-ground footing systems are derived from the waffle pod footing system. For instance, a two-way post-tensioned waffle pod footing system was designed to decrease the slab thickness and suffice ductility requirements [19]. Other footing systems derived from the generic waffle pod has EPS spanning across the entire floor area to provide passive insulation for houses. [21] developed modular formworks, which are laid out on the ground and then concrete is poured. Likewise, a polyethylene formwork similar to the shape of the EPS of waffle pods was developed to ease the placement of reinforcing bars, steel mesh and concrete. A dome formwork (Figure 9), on the other hand, has a mould with cone support at the middle. Each dome inter-connects, providing a supplementary damp-proofing for capillary action with impervious liners. Additional reinforced beams or piles are used for sites with reactive soils.

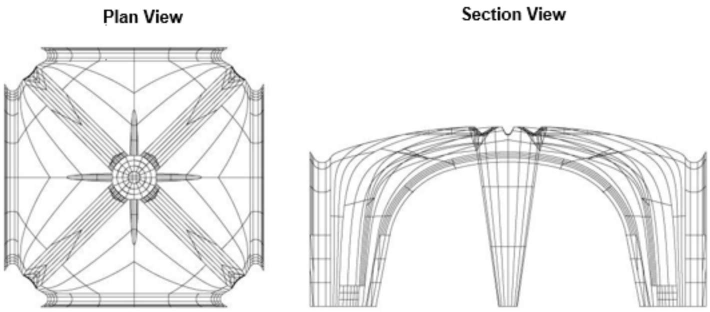

Figure 9. An on-ground permanent dome formwork footing system.

Shallow footing systems are typically used for houses due to their affordability. The most commonly used are the stiffened raft slab and waffle pod rafts. Despite the popularity of the stiffened raft and waffle pods, there are a significant number of emerging technologies related to shallow footings due to the need for better quality and faster construction. These innovative footings use prefabricated isolated footings or prefabricated strip footings, apply block piers, pods, anchors, bracings and chassis beams, deploy beam clamps, structural panels and deadman, and utilise integrated formwork. Nonetheless, soils are sometimes expansive or do not have sufficient bearing capacity to carry overburden pressures. Thus, deep footing systems may be an option to reduce deformation that may damage not only the footing system but also the remainder of the house.

2.2. Deep footing systems

Deep footing systems can reduce the total and the differential settlement of houses by transferring applied structure loads to a deeper and stronger subsurface layer. The depth-to-width ratios of these systems are equal to or greater than 5.0. These systems cost more since more materials are needed to and cause greater site disturbance and require skilful installations using heavy or specialised handheld equipment. Deep footing systems available for houses are displacement or non-displacement piles, micropiles with a head cap, an integrated wall and footing system, and permanent pier formwork.

2.2.1. Prefabricated piles with modular beams

The first type of deep footings is the prefabricated, in-situ concrete or steel screw piles with modular beams, which is one of the most recommended systems in the market (Figure 10). This footing is suggested to have a gap underneath the slab to isolate the system and reduce deformation due to shrinking and swelling of an expansive soil underneath [22]. Piles are driven first and then prefabricated beams are connected. Most installations post-tension the prefabricated concrete beams on-site to create a rigid, homogenous footing system applicable to variety of structures. Some installations drive piles and then connect the prefabricated beams and modular blocks. The

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prefabricated beams and modular blocks have dowels for easier placement. A cement grout is then poured after placement to ensure a continuous connection and monolithic behaviour of the footing system.

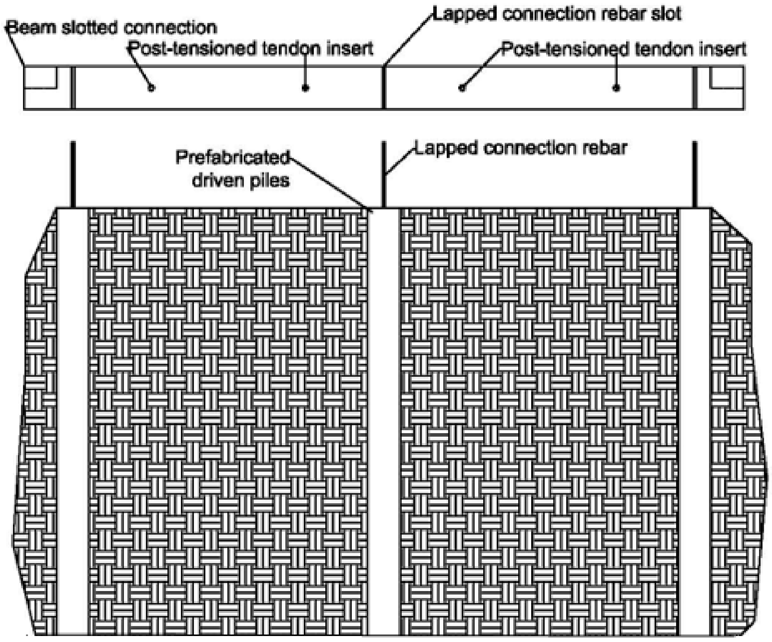

Figure 10. An on-ground permanent dome formwork footing system.

2.2.2. Micropile systems with pile caps

Another deep footing system is a micropile system, which is a solid pin footing that is embedded deep into the ground without digging holes or pouring concrete (Figure 11). It is comprised of precast concrete or reticulated steel head installed on the ground surface, the steel bearing micropile are driven through the head using specialised hand-held tools. However, this footing system can only carry light structures such as decks, boardwalks, trails and pedestrian bridges. Further design analysis should be performed for housing application. It may also be challenging to drive into hard soil strata, which may cause initial deflection due to installation. Another variation of the micropile system uses multi-directional pin caps and piles, which provide support to the superstructure by resisting vertical loads including uplift, shear and moment loads.

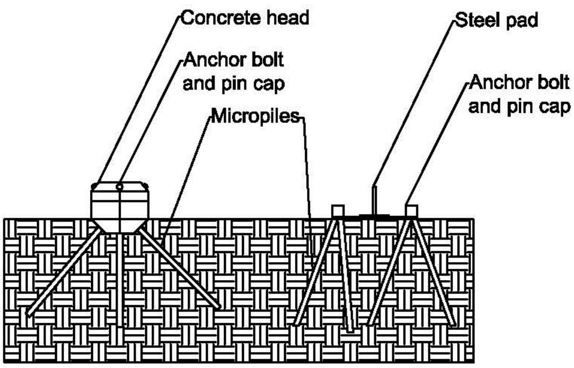

Figure 11. Micropiles with concrete head and anchor bolt and a reticulated micropiles with steel pad.

2.2.3. Integrated wall and footing system

An alternative deep footing system is an integrated wall and footing system, which also serves as a basement. The integrated wall and footing system is constructed off-site using a high-strength, low-water concrete with no additional damp-proofing required. The foundation wall is monolithically poured for a solid structure with steel reinforcements and polypropylene fibres (Figure 12). [5] also developed a similar footing system that is efficiently constructed in harsh climates. This footing system also reduces the active depth of expansive soils prone to moisture changes by excavating the ground for a basement. Nevertheless, it is prone to lateral pore water pressure that necessitates the installation of drain pipes to reduce the moisture and stress experienced by the walls.

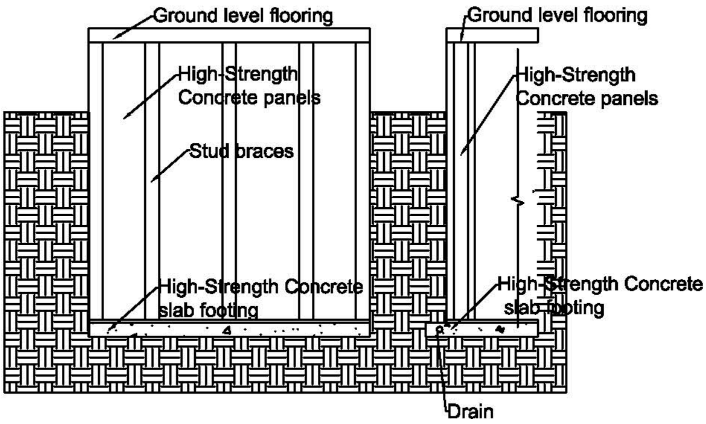

Figure 12. Prefabricated basement foundation using an integrated wall and footing system installed in an excavation [5].

2.2.4. Permanent pier formwork

An integrated formwork footing system can also be used for houses. Permanent formwork was developed to easily pour concrete into the moulds and to control the quality of footings. The form is installed with body snaps together with no additional specialised tools required. However, manual labour is needed for excavating the soil. The first type of integrated formwork is the permanent formwork for pier footings. Custom-fabricated vertical and horizontal rebars can also be placed using the rebar holder in- side the form (Figure 13). The integrated rebar holder reduces the amount of concrete needed and properly locates and holds rebars. However, since this formwork only has one available dimension, there will be limited options that may cause an inefficient design for a set of footings of a prefabricated house.

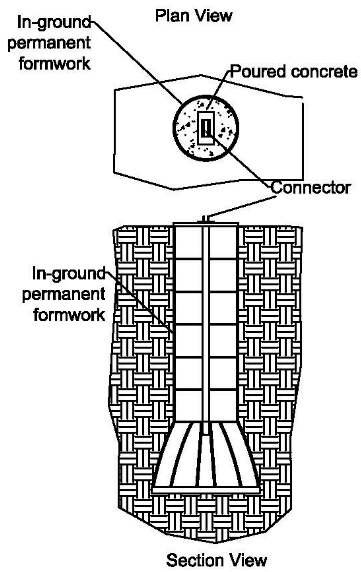

Figure 13. A permanent pier formwork with cast-in-place concrete.

Deep footing systems are effective on reducing deformation experienced by a house due to a stiffer and more stable support installed through deeper soils with less soil moisture variability. The types of deep footings are driven piles with interlocking beams, micropiles with cap head and integrated wall and footing systems as basements. Although structurally robust, deep footings are typically more expensive relative to shallow footing due to a greater quantity of materials and labour required, as specialised equipment needed for construction.

3. Prefabricated footing design

A design of an ideal prefabricated footing solution based on the reviewed innovative footing systems is presented in this section considering the applications for low-rise and light-weight residential structures classified as single dwelling house, townhouse, or similar structure (Class 1 and Class 10a,[14,23] while considering the reactive soil conditions. To develop an ideal design, consideration of factors including structural design, manufacturing design, handling and transportation of goods, assembly process and system sustainability, which affect the integrity of the footing system, total cost and construction lead time [13]. The factors considered in designing an ideal prefabricated footing system are discussed in this section.

3.1. Structural design requirements

An ideal design of a prefabricated footing solution should have mechanism to adapt with different site classifications (Table 1, AS 2870-2011), specifically sites with reactive soils. These soils have high potential to change their volume depending on the presence and characteristics of clay particles and soil moisture, shrinking with soil moisture decrease and swelling with soil moisture increase. The interaction between soils and footing system is affected by weather factors (i.e. soil suction change), oil factors (i.e. soil modulus, shrink-swell index, hydraulic conductivity), active depth zone where ground movement extends [24] and loading factors [25,25,26]. The approaches to prevent substantial amount of damage [27], not only to footing systems but also for the superstructure elements of houses (i.e. walls, ceilings, frames, slabs designed base on [28–30], are either (1) to stiffen the footing systems or (2) to isolate the superstructure.

Stiffening of footing systems are implemented to resist soil movement [22], which is effective to site classes A, S and M. With site classes having highly reactive soils. Most stiffened footing systems used for residential applications are stiffened rafts (2.1.1), braced masonry with metal straps (2.1.3), structural panel wall support (2.1.5) and integrated wall and footing system (2.2.3). Stiffening of footing systems can be costly to prevent severe cracking. For instance, stiffened rafts have deeper beam depths and thicker slab compared to waffle pod rafts to resist the shrink-swell ground movement [15]. Likewise, braced masonry with metal straps is stiffened using the distribution of loads through tension. However, redundant metal straps are used to over-engineer and prevent failure of this system. On the other hand, structural panel wall support is stiffened using a composite concrete wall covered with corrugated metal and integrated wall and footing system is stiffened using High-Strength Concrete (HSC) with stud patterns. These two systems are effective in reducing the shrink-swell ground movement through reducing the active depth zone by excavation [5]. However, well-planned drainage should be installed. Most stiffened footing systems discussed are labour and material intensive, which affect the cost-efficiency [31,32]. If stiffening of the footing system of a house is not cost-efficient, isolation of the superstructure can be considered.

Isolation of the superstructure is achieved by installing a system with minimum contact area between footings and founding ground. Isolated footing system can either be embedded shallowly or deeply into the ground. Shallow isolated footing systems are piers, pads and ground anchor system (2.1.2), piers and beam clamps (2.1.4), telescoping arm with deadman (2.1.6), semi-adjustable columns (2.1.7), waffle pod raft (2.1.8) and on-ground permanent formwork systems (2.1.9). These footing systems are mostly comprised of piers and pads acting as stumps for isolation with anchors (i.e. ground anchors, beam clamps and deadman) to prevent overturning. Some of these footing systems use formwork to avoid soil-structure interaction (e.g. waffle pod raft and on-ground permanent formwork systems). Isolated footings are recommended to stable ground since when these are installed in reactive sites, there will be insufficient support embedded in the ground and insufficient stiffness to resist ground movements leading to possible structural damage. Deep isolated footing systems are prefabricated piles with modular beams (2.2.1), micropile systems (2.2.2) and permanent pier formwork (2.2.3). These systems extend through the stable part of a soil profile to anchor a residential structure. However, extending the footing system to the inactive depth zone is costly but effective to prevent damage due to the shrink-swell ground movement [22].

In summary, the ideal structural design of a prefabricated footing is aptly developing a system with structural integrity yet economical. From the review of different footing systems, isolation of residential structures to reduce the soil-structure interaction are commonly used. [15–17]. An ideal prefabricated solution would be a deep isolated footing system, which has sufficient anchorage protruding into a soil profile. This ideal prefabricated solution shall have competitive cost and can be rapidly constructed on-site without any special requirements for installation (e.g. equipment, levelling, curing).

3.2. Manufacturing requirements

Balancing the structural integrity and cost of a system is challenging to achieve to develop an ideal prefabricated solution. A possible key to achieve this goal is to apply optimised manufacturing, a systematic method to minimise material usage and waste disposal [33,34]. Optimised manufacturing does not only reduce the cost through material and waste reduction, this also enhances the end product and process efficiencies [13,35]. To maximise the benefit given by a optimised prefabricated footing system, it is important that the manufacturing processes are considered thoroughly from the design outset. Based from past studies, it is well proven that the optimised philosophy enable successful results with design, manufacturing and assembly considerations [34]. The philosophy of thinking optimisation permits manufacturing in controlled factory conditions, leading to a more efficient and safe construction of prefabricated footings assembled on-site [36].

Another important consideration for an ideal prefabricated solution is using dimensional coordination. Dimensional coordination is a manufacturing tool to organise different elements independently to be connected and integrated as a whole [37,38]. This method does not only improve the assembly of a structure considering strict tolerance, this also improves the flexibility of material usage and practicality of design [39]. Modular coordination is defined as the definitive goal of dimensional coordination, which will help to industrialise footing systems through prefabrication [40]. Modular coordination, together with optimised manufacturing, permits advantageous usage of materials, hence, reducing material and total cost.

3.3. Handling and transportation requirements

An ideal prefabricated footing solution shall be safe and easy to handle [41–43] and to transport [44–46]. Handling and transportation are areas in particular where prefabricated footing systems introduce novel considerations [47]. These considerations include lifting of prefabricated elements [48], packaging [49], transportation load restraints [50], safe containers [51] and proper documentation. The constraint in transportation due to the vehicle size may also limit the dimension of prefabricated footing systems. Furthermore, weight restrictions and site access for cranes should be taken into account [13].

3.4. Assembly requirements

The main challenges of a prefabricated solution are (1) to have a rapid installation on-site without any labour-intensive process and (2) to have proper tolerance for ease of installation. On-site rapid installation of prefabricated solutions should comply with safety work guidelines [52–54], neglect non-essential earthwork (e.g. levelling) [55] and disregard unnecessary temporary structures (e.g. formwork) [56]. Although labour is much less intensive for prefabricated footing solutions, specialised skills for assembly are required [57]. For ease of installation during the assembly stage, tolerance should be well-considered in the design outset and manufacturing [58]. The superstructure shall be positioned ensuring that the alignment of actual connection locations of the footing system are within acceptable tolerance [59]. The assembly of joints and connections shall also have strict tolerance and must fit aptly with the elements being connected [60,61]. Furthermore, it is advisable for an ideal prefabricated footing system can be reused without compromising the structural integrity of an entire residential structure [62]. A suggested conceptual design considering design for manufacturing and assembly is presented in the succeeding section.

3.5. Summary and conceptual designs

Developing ideal prefabricated footing systems shall consider structural design, manufacturing, handling, transportation and assembly. Ideal prefabricated solutions would be a deep isolated footing system with sufficient anchorage into a soil profile or a partially suspended footing system on-ground. These ideal prefabricated solutions shall have competitive cost and can be rapidly constructed on-site without any special requirements for installation (e.g. equipment or curing). To balance the structural integrity and cost, without over-engineering, the philosophy of optimised manufacturing and modular coordination shall be applied. Furthermore, this ideal prefabricated footing system shall be safe and easy to handle and transport, which can be assembled rapidly on-site with minimum labour requirements and proper tolerance.

The prefabricated footing system will seek to minimise site disturbance through off-site manufacturing of elements. This solution will also minimise on-site assembly requirements, which will expedite construction, through an easy-to-install micropiles, soil screws or ground anchors. Furthermore, an adjustable connection between micropiles, soil screws or ground anchors and I-beams, prefabricated reinforced beams or timber beams disregard the necessity for earthwork (i.e. ground levelling, cut and fill). A prefabricated reinforced slab or a timber deck will be suspended to isolate the residential structure, reducing the soil-structure interaction and probable structural damage (i.e. slab, wall and ceiling cracks). This system is suggested to be structurally robust made using light-weight materials aptly fitting each other with strict tolerance. However, cost can be an issue if structural elements are suspended on piers due to higher stiffness element requirements.

Partially-suspended prefabricated structural elements on levelled ground may be more economical than prefabricated isolated footing systems, specifically for stable to moderately reactive sites. However, concrete piles or screw piles may be required for highly reactive sites. Thus, the system requirements practicality varies depending on the soil condition of a site.

4. Advantages of prefabricated footing solutions

The benefits of using innovative and prefabricated footings shall be recognised to know their feasibility to be prevalent in the future construction practices. The advantages of prefabricated systems depend on the building type and quantity for installation affecting the design viability, construction speed and footing cost. Furthermore, additional benefits are better material quality control, fewer risks and a more sustainable construction method. This section provides a critical review of the benefits of innovative and prefabricated footings based on studies related to this topic and further discuss the potential footing systems which prefabrication can be incorporated.

If the building type of the structure to be built is a low-rise lightweight and a large concrete volume is to be installed, prefabricated footings will be an advantageous choice. Prefabricated footings are more practical if implemented with low-rise lightweight structures such as prefabricated houses, this application is more technically feasible compared to tall and heavy buildings due to lower loads involved [63]. The quantity being installed also plays an important role to achieve significant savings [64]. Prefabricated footings in residential schemes is a suitable alternative for large-scale construction since handling and transportation costs are important considerations, which are reduced when installed in large volumes [65]. When dealing with a large-scale project, the lead time of footing installation may be reduced since the components are efficiently procured and readily assembled on-site [64]. This in turn allows onsite work to commence on the superstructure sooner.

With the use of innovative and prefabricated footings, the construction period may be considerably reduced. The lead time for formwork installation, concrete curing and formwork decommissioning in constructing traditional cast-in-place residential footings are eliminated [5,18]. The delays due to inclement weather will also be prevented through effective planning and efficient procurement [63]. In addition, the delays due to different material delivery schedules are not experienced since the components of prefabricated footings are delivered altogether and the only on-site process needing to take place is assembly. Furthermore, reduction of the construction period also reduces the disturbance of the construction work on the surrounding environment and decreases unexpected expenses [66]. Conventional construction period of houses is around seven to twelve months where footing system construction may not have much significance. However, for prefabricated residential structures, the construction period is significantly shorter than the conventional way of constructing houses, hence, prefabricated footing system is more suitable for a faster construction lead time.

The price of prefabrication is easier to control since it is fixed and has lesser unexpected costs [66]. Furthermore, if prefabricated footings are industrialised, substantial savings can further decrease the direct cost due to large-scale production without compromising their quality [63].

Prefabrication usually lead to a quality-controlled construction. The materials being used are commonly of better quality, the staff are well-trained and specialised, and the quality of prefabricated products and processes are consistently supervised and checked [67]. The manufacturing process has lesser possibilities for human error compared to in-situ construction. Thus, the quality of prefabricated products offers lesser uncertainty in assembly and footing price due to fewer incidents and more durable prefabricated components [66].

Prefabricated footing construction will provide better working conditions reducing accident risks and more stable environment [11]. There are also fewer subcontractors involved that simplifies management, conflicts and delays [66]. The scope of work is more consistent in prefabrication and assembly unlike in conventional construction where there are seasonal fluctuations in labour depending on the stage of the construction [63].

Innovative and prefabricated footing systems may avoid over-dimensioning and promote reusing and recycling, leading to a more sustainable option. Most prefabricated components applied value engineering to reduce material wastage preventing over-dimensioning, which reduces the amount of resources and energy used [11]. Furthermore, most prefabricated systems are manufactured based on optimised design and production, which reduces carbon emissions to the atmosphere [64]. Most prefabricated systems might also be dismantled instead of demolishing the whole footing due to its modular design, encouraging the reuse and recycle of the modules [11]. Some prefabricated footings may also be constructed using recycled materials and some parts such as void formers can be reused, which reduces the carbon footprint, cost and resource requirements of the systems [18,68].

The aforementioned advantages of innovative and prefabricated footing systems will help solve the issues of housing affordability and shortage. A shorter construction lead time will increase the number of house completion having better quality and lower unexpected costs compared to some traditional cast-in-place footing systems, which also does not rely on skilled labour shortage. Furthermore, prefabricated footing systems saves a significant amount of time since these can be installed immediately after being delivered on site, removing the need for curing period. In summary, the advantages of constructing innovative and prefabricated footings are reduced construction period, controlled material and labour costs, improved quality and increased sustainability. The feasibility of industrialised prefabricated footings will further be discussed in the next section by tackling the challenges that may be encountered in designing and constructing novel and prefabricated components.

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5. Challenges in industrialising prefabricated footings

Prefabrication of footing systems have positive impacts on the Australian residential construction industry. However, product design studies and industry applications of novel footing systems are lacking not only in Australia but also globally. Footings are still constructed using the conventional cast-in-place method due to challenges being encountered in industrialising prefabricated footing systems. The major challenges include industry scepticism, capital or initial investments, technological limitations, procurement limitations, reactive soil conditions and optimized panel design and connection.

The knowledge and training of the construction industry is still bound by tradition and its scepticism has been affecting the gradual progress of prefabricated footings [18], which is evident in the present Australian context. The majority of prefabricated houses are presently being built on conventional footings, this reflects the wide development gap between the superstructure and the substructure of the prefabricated construction industry. Practitioners do not trust the industrialisation of prefabricated houses to the extent of constructing prefabricated footings that act as the main support of a house [69]. This scepticism of companies is due to greater risks and considerable liabilities that may arise if novel methods fail. Therefore, companies tend to use conventional methods with tested solutions preventing more investments due to research and development, equipment cost and organisational expenditure [63]. A design practice standard for designing and constructing prefabricated footing systems for houses is still not available sue to challenging performance monitoring of modular houses and their complex connections.

The government regulations and client initiatives also play their roles in the gradual progress of prefabricated footings. The government only has regulations for familiar solutions [11]. Furthermore, clients see their houses as long-term investments and they are risk-averse to trying novel and innovative solutions. Clients, builders and investors prefer materials and construction solutions that have a proven track record. Furthermore, the direct cost of prefabricated footings has been reported to be higher than that of the conventional cast-in-place footings by 5% to 30% due to material, manufacturing, and transport costs [5,11]. Footing systems are possibly the most important structural part of most buildings but a substructure with more affordable direct cost is more preferable by clients than a costly, convenient and sustainable one [63]. Hence, the long period needed in monitoring durability and the relative high cost of a prefabricated footing is hindering innovation and industrialisation.

Design challenges such as specificity and coordination are some issues considered in developing modular prefabricated footings. Footings are usually designed depending on the geometry and structural configuration of the superstructure of the house and the site classification. Footing designs are often made specifically for unique combinations of loads, soil classification and climate zone, which may be challenging to create a repetitive modular design that will be applicable to most situations [21]. Furthermore, dimensional variety is inevitable due to the differences of the magnitude of loads along the structural spans [69].

The design of modular footing systems shall consider transport and procurement. Prefabricated footings shall be handled carefully and delivered in a pristine condition. Logistically, prefabricated footings are potentially more challenging to transport. Hence, it is advisable that it has a stackable design to optimise the space in a factory and a delivery truck. In addition, the transportation is costly and the economical delivery radius from the factory may vary depending on the location and region [5]

Prefabricated footings are constructed on-site by assembling the delivered parts from a factory. To obtain an effective assembly, the connection between the substructure and superstructure should have a panelised joint connection that reduces wall and slab cracks due to ground movements. Joint connections are the most critical part specifically when the structure is subjected to dynamic loads, which may limit the use of prefabricated footings in areas prone to ground movements and cyclic soil swelling and shrinking [21].

6. Conclusions and recommendations

The consistently strong Australian economy and stable population growth have led to a higher demand for residential structures. The full potential of prefabricated construction cannot be achieved without addressing opportunities to prefabricate the substructure. Prefabrication of footing systems has the potential to significantly improve construction quality, construction time and sustainability. This may also reduce construction delays, labour shortages and unexpected expenses. Prefabrication also provide opportunities to employees from automotive industry to transfer their manufacturing and assembly knowledge to the prefabricated housing industry. Thus, this paper presented the existing innovative footings available for prefabricated houses and reviewed the advantages and challenges of constructing and industrialising innovative prefabricated footing solutions.

The type of footing to be used in a site depends on different factors. Important factors to be considered are the susceptibility of a site to ground movements due to shrinking and swelling of soils, the budget allocated for the footing system and the time necessary to complete the structure. The effectiveness of shallow footings and deep footings depends on these three main considerations. Clients usually settle for a footing system with a lower direct cost rather than choosing a costly, faster and more sustainable option since both can adequately support a house.

Innovative and prefabricated footing systems offer a faster construction, which will increase the number of house completion having better quality and lower unexpected costs compared to a traditional cast-in-place footing system. However, there are still challenges needed to be solved. The primary challenges in industrialising prefabricated footing systems include the scepticism of the construction industry, government and end clients due to higher financial and safety risks associated with novel design and construction. Furthermore, a more reliable and durable design of a footing system that responds to the aforementioned design challenges and procurement limitations may not have been invented yet. These reasons hinder the progress of innovative footing system industry for prefabricated houses. A general conceptual design that can be assembled within a day is suggested in this review, which considers the structural design, manufacturing, handling, transporting and assembly minimising site disturbance and on-site assembly requirements, whilst remaining cost-competitive with existing footings available in the current market.

Author Contributions: Conceptualization, B.T., S.K.B and D.H..; Methodology, B.T.; Resources, P.M., T.D.N. and M.T.; Writing-Original Draft Preparation, B.T.; Writing-Review & Editing, B.T., D.H. and S.K.B.; Supervision, P.M., T.D.N. and D.H.; Project Administration, M.T. and S.K.B.; Funding Acquisition, M.T., P.M. and T.D.N.

Funding: This research was funded by Australian Research Council (ARC) Training Centre for Advanced Manufacturing of Prefabricated Housing with Project ID IC150100030.

Acknowledgments: The authors would like to acknowledge the support of the Australian Research Council – Centre for Advanced Manufacturing of Prefabricated Housing (ARC-CAMPH) and The Australian Reinforcing Company.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Stapledon, N. A History of Housing Prices in Australia 1880-2010. **2010**.
2. Australian Bureau of Statistics Australian Bureau of Statistics: Building Approvals Available online: http://www.abs.gov.au/Ausstats/abs@.nsf/mf/8731.0 (accessed on Sep 6, 2017).
3. Cannington, D. *Australian Property: Australian Housing Chartbook*; 2017; p. 11;.
4. Lewis, K. HIA Trades Report September 2017 Quarter. **2017**, 6.
5. Yu, H.; Al-Hussein, M.; Nasseri, R.; Cheng, R. J. Sustainable precast concrete foundation system for residential construction. *Canadian Journal of Civil Engineering* **2008**, *35*, 190–199.

6. Lichtenberg, J. Slimbouwen, a strategy for efficient and sustainable building innovation. In *Proceedings Joint*; 2006.
7. Gibb, A. G. *Off-site fabrication: prefabrication, pre-assembly and modularisation*; John Wiley & Sons, 1999;
8. Barlow, J.; Ozaki, R. Building mass customised housing through innovation in the production system: lessons from Japan. *Environment and Planning A* **2005**, *37*, 9–20.
9. Song, J.; Fagerlund, W. R.; Haas, C. T.; Tatum, C. B.; Vanegas, J. A. Considering prework on industrial projects. *Journal of construction engineering and management* **2005**, *131*, 723–733.
10. Friedman, A. Prefabrication versus conventional construction in single-family wood-frame housing: Costs of conventional and prefabricated Canadian homes compared in a survey of 15 manufacturers in the provinces of Quebec and Ontario. *Building Research & Information* **1992**, *20*, 226–228, doi:10.1080/09613219208727210.
11. Pujadas Gispert, E. Prefabricated foundtions for housing applied to room modules, 2016.
12. Nelson, S. Modular housing: prefab and proudly upmarket. *Building Connection* **2008**, 24.
13. Monash University *Handbook for the design of modular structures*; 2017; ISBN 978-0-646-96498-0.
14. Australian Building Codes Board *National Construction Code 2016 Volume Two Building Code of Australia Class 1 and Class 10 Buildings*; Canberra, 2016;
15. Standards Australia *Residential slabs and footings*; Standards Australia: Sydney, N.S.W., 2011; ISBN 978-0-7337-9756-9.
16. Manufactured Housing Research Alliance Guide to foundation and support systems for manufactured homes 2002.
17. Federal Emergency Management Agency *Protecting manufactured homes from floods and other hazards*; 2009;
18. Moonen, S. P. G.; Hermans, K. Building with materials from demolition projects. In *Proceedings of the 11th International Detail Design in Architecture (DDiA) Conference*; 2013; Vol. 21, p. 22.
19. Moldovan, I.; Mathe, A. A Study on a two-way post-tensioned concrete waffle slab. *Procedia Technology* **2016**, *22*, 227–234, doi:10.1016/j.protcy.2016.01.072.
20. Kivi, A. K. Evaluation of structural dome formwork systems in concrete pavement applications, University of Waterloo, 2013.
21. Marquez, A. Componente modular prefabricado de concreto para placa defundacion superficial reticular alveolada. *Tecnologia y Construccion* **2012**, *22*, 23–33.
22. Far, H.; Flint, D. Significance of using isolated footing technique for residential construction on expansive soils. *Frontiers of Structural and Civil Engineering* **2017**, *11*, 123–129, doi:10.1007/s11709-016-0372-8.
23. Victorian Legislation Building Act 1993 1993.
24. Briaud, J.-L.; Abdelmalak, R.; Zhang, X.; Magbo, C. Stiffened slab-on-grade on shrink-swell soil: new design method. *Journal of Geotechnical and Geoenvironmental Engineering* **2016**, *142*, 04016017, doi:10.1061/(ASCE)GT.1943-5606.0001460.
25. Standards Australia *Structural design actions. Part 1, Part 1,*; Standards Australia ; Standards New Zealand: Sydney, N.S.W.; Wellington [N.Z., 2012;
26. Standards Australia *Structural design actions.*; Standards Australia ; Standards New Zealand: Homebush, NSW; Wellington, N.Z., 2002; ISBN 978-1-86975-020-6.
27. Gad, E. *Building Connection*. 2016, p. 14.

28. Standards Australia *Timber structures. Part 1, Part 1,*; Standards Australia: North Sydney, N.S.W., 2011; ISBN 978-0-7337-9429-2.
29. Standards Australia *Concrete structures: AS 3600-2009.*; Standards Australia: Homebush, N.S.W., 2009; ISBN 978-0-7337-9347-9.
30. Standards Australia *Australian Standard: steel structures.*; Standards Australia: Homebush, NSW, 1998; ISBN 978-0-7337-1981-3.
31. Sebastian, R. Low Disturbance Urban Projects through Smart Manufacturing and BIM Availableonline: https://www.researchgate.net/publication/236208837_Low_Disturbance_Urban_Projects_through_Smart_Manufacturing_and_BIM (accessed on May 21, 2018).
32. Sebastian, R.; Claeson-Jonsson, C.; Di Giulio, R. Performance-based procurement for low-disturbance bridge construction projects. *Construction Innovation* **2013**, *13*, 394–409.
33. Dilanthi, M. G. S. Conceptual Evolution of Lean Manufacturing. **2015**.
34. McFarlane, A.; Stehle, J. DfMA: engineering the future. In *Proceedings of Council on Tall Buildings and Urban Habitat (CTBUH) 2014 Shanghai Conference*; 2014; Vol. 16, pp. 508–516.
35. Standards Australia *Quality Management systems -- requirements*; Standards Australia Limited ; Standards New Zealand: Sydney, NSW.; Wellington [N.Z., 2016; ISBN 978-1-76035-422-0.
36. Yu, H.; Al-Hussein, M.; Al-Jibouri, S.; Telyas, A. Lean Transformation in a Modular Building Company: A Case for Implementation. *Journal of Management in Engineering* **2013**, *29*, 103–111, doi:10.1061/(ASCE)ME.1943-5479.0000115.
37. American Society for Testing and Materials Standard Guide for Dimensional Coordination of Rectilinear Building Parts and Sysems 2002.
38. Bergvall, L. Dimensional coordination as a tool for industrialisation. In *Metric Dimensional Coordination - The Issue and Precedent*; 1977.
39. Adams, M. W.; Bradley†, P. Dimensional Coordination *. *Journal of the American Ceramic Society* **1945**, *28*, 217–226, doi:10.1111/j.1151-2916.1945.tb14538.x.
40. Leung, Y. Dimensional coordination of industrialized metal buildings. Thesis, 1971.
41. Australian Government Work Health and Safety Act 2011 2011.
42. Victorian Legislation Occupational Health and Safety Regulations 2007 2007.
43. Victorian Legislation Occupational Health and Safety Act 2004 2004.
44. Brassington, B. Code of Practice for Packing of Cargo Transport Units 2012.
45. Commonwealth Heavy Vehicle National Law 2011.
46. Commonwealth Road Transport Reform (Mass and Loading) Regulations 1995.
47. Beck, W. G. Prefabricated modular concrete foundation wall systems and methods of constructing prefabricated modular concrete foundation wall systems 1999.
48. Standards Australia *AS 1418.1 1986: Cranes, hoists and winches - Part 1 general requirements.*; Standards Australia: Sydney, 1986; ISBN 978-0-7337-4372-6.
49. Australasian Procurement and Construction Council *Procurement of Construction Products - a guide to achieving compliance*; 2014; ISBN 978-0-9925423-1-3.
50. National Transport Commission; National Transport Commission; Roads and Traffic Authority of New South Wales *Load restraint guide: guidelines and performance standards for the safe carriage of loads on road vehicles.*; National Transport Commission: Melbourne, 2004; ISBN 978-0-7313-0134-8.

51. International Maritime Organization Revised recommendations on harmonized interpretation and implementation of the iternational convention for safe containers (CSC) 2013.
52. SafeWork Australia *Safe design of structures: code of practice.*; Safe Work Australia, 2012; ISBN 978-0-642-78546-6.
53. WorkSafe Victoria *Guide to the Occupational Health and Safety Regulations*; 2017;
54. WorkSafe Victoria *Working safely in the general construction industry - a handbook for the construction regulations*; 2008;
55. Cement and Concrete Association of Australia *Guide to residential floors*; Cement and Concrete Association of Australia: St Leonards, NSW, 2003; ISBN 978-1-877023-07-1.
56. Australian Building Codes Board *Temporary Structures Standard*; 2015;
57. Vokes, C.; Brennan, J. Technology and skills in the Construction Industry: Evidence Report 74 2014.
58. Face, S. A.; Heist, T. C.; Kaden, R. A.; Martin, R.; Meza, P.; Morcos, A.; Morgan, C. B.; Palmbaum, H. M.; Phelan, W. S.; Pointer, B. J.; Stephan, D. E.; Tipping, E.; Togni, C. S.; Williams, J. V. 117-90 Standard Specifications for Tolerances for Concrete Construction and Materials. **2002**, 12.
59. American Concrete Institute 117-06 Specifications for Tolerances for Concrete Construction and Materials. **2002**, 70.
60. Jaspart, J.-P.; Weynand, K. Design of joints i steel and composite structures. **2016**.
61. Jaspart, J.-P.; Weynand, K. Design of Joints in Steel and Composite Structures: Eurocode 3: Design of Steel Structures, Part 1-8–Design of Joints, Eurocode 4: Design of Composite Steel and Concrete Structures, Part 1-1–General Rules and Rules for Buildings. In; Wiley Online Library, 2016.
62. Department of Sustainability, Environment, Water, Population and Communities *Construction and demolition waste guide - Recycling and Reuse across the supply chain*; 2012;
63. Kumar, V. K. Industrialized foundations for low-rise light-weight buildings, Virginia Polytechnic Institute and State University, 1972.
64. Wren, C. Chapter 91 Modular foundations and retaining walls. In *ICE manual of geotechnical engineering*; Thomas Telford Ltd, 2012; pp. 1343–1350.
65. Huat, B. B.; Mohammed, T. A. Finite element study using FE code (PLAXIS) on the geotechnical behavior of shell footings. *Journal of Computer Science* **2006**, *2*, 104–108.
66. Escrig Pérez, C. Evolución de los sistemas de construcción industrializados a base de elementos prefabricados de hormigón. **2010**.
67. Venables, T.; Courtney, R. Modern methods of construction in Germany. *UK: Pera Innovation Limited.(Department of Trade and Industry (DTI)) Capítulo* **2004**, *6*, 2860–2871.
68. Moonen, S. P. G. Rapidly building with lightweight modules and a dry assembled foundation: used in a mock-up for home units made out of reclaimed materials. In; 2014; pp. 209–221.
69. Llorens Duran, J. I. de; Pujadas Gispert, E. Lightweight recoverable foundations on suitable ground. In *World sustainable building 2014 Barcelona conference*; Green Building Council España, 2015; pp. 1–7.
70. All Steel Foundation System : Oliver Technologies Inc. Available online: http://www.olivertechnologies.com/all-steel-foundation-systems.html (accessed on May 23, 2018).
71. Cupolex Building Systems Australia | Concrete Flooring | Dome Concrete Slab Available online: http://www.cupolex.com.au/ (accessed on Sep 5, 2016).

72. Cupolex Canada Available online: http://www.pontarolo.ca/html/cupolexapp.shtml (accessed on Dec 7, 2016).
73. Cupolex Manual.
74. Diamond Pier Available online: http://pinfoundations.com/ (accessed on May 23, 2018).
75. Diamond Pod™ Void Formers from Foamex Available online: http://www.foamex.com.au/polystyrene-products/foamex-diamond-pods-waffle-pods (accessed on Sep 5, 2016).
76. Fast Track's Anchorpanel System Overview Available online: http://www.anchorpanel.com/ (accessed on May 23, 2018).
77. Foundations | Ecocor | Pre-Fab Passive House Available online: https://www.ecocor.us/foundations (accessed on May 23, 2018).
78. Krinner Ground Screws Australia Available online: http://www.krinner.com.au/ (accessed on May 23, 2018).
79. Mega Anchor Available online: https://www.mega-anchor.com.au/ (accessed on May 23, 2018).
80. Multipoint Foundations Available online: http://multipoint-foundations.com/index.html (accessed on May 23, 2018).
81. Passive House Foundations, Insulated Foundations Available online: http://viking-house.ie/passive-house-foundations.html (accessed on May 23, 2018).
82. Projects - Foundations Guide Available online: https://www.research-alliance.org/pages/foundations_guide.htm (accessed on May 23, 2018).
83. Screw Pile Foundations Melbourne | Screw Pile Footing | Steel Footing | Surefoot Available online: https://surefootfootings.com.au/ (accessed on May 23, 2018).
84. The Anchor Post Website Available online: http://stormanchor.com/ (accessed on May 23, 2018).
85. Vector D Available online: https://www.yumpu.com/en/document/view/29147006/vector-foundation-system-with-engineers-seal-tie-down-/4 (accessed on May 23, 2018).
86. Xi2 Foundation System Sales Flyer (PDF) - Tie Down Engineering Available online: https://www.yumpu.com/en/document/view/30078294/xi2-foundation-system-sales-flyer-pdf-tie-down-engineering (accessed on May 23, 2018).
87. Daley, J.; Coates, B.; Wiltshire, T.; Grattan Institute *Housing affordability: re-imagining the Australian dream*; Grattan Institute: Carlton, 2018; ISBN 978-0-648-23074-8.
88. Homer, H. D. Retaining wall and section thereof 1965.
89. InnoTecTrading *Krinner Ground Screws - THE foundation system for solar projects*; 2010;
90. Jaillon, L.; Poon, C. S. The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector. *Automation in Construction* **2009**, *18*, 239–248.
91. Jeff Gutterud *Pin Foundations Diamond Pier Overview As Seen on Public Television's Hometime*; 2011;
92. Mehdizadeh, A.; Disfani, M. M.; Evans, R.; Gad, E.; Escobar, A.; Jennings, W. Static Load Testing of Concrete Free Reticulated Micropiles System. In.
93. Ong, R.; Dalton, T.; Gurran, N.; Phelps, C.; Rowley, S.; Wood, G.; AHURI LTD *Housing supply responsiveness in Australia: distribution, drivers and institutional settings*; Australian Housing and Urban Research Institute Limited, 2017;

 doi:10.20944/preprints201807.0441.v1

94. RMIT Features of waffle raft slabs Available online: https://emedia.rmit.edu.au/dlsweb/Toolbox/buildright/content/bcgbc4010a/09_footing_systems/06_concrete_slabs/page_006.htm (accessed on May 17, 2018).
95. ScrewFastFoundations *ScrewFast Foundations Innovative GRIP® Pile Foundation*; 2010;
96. Sun, X.; Li, J.; Ren, G. Residential footing design on expansive soils: a review of Australian practice. *Electronic Journal of Geotechnical Engineering* **2017**, *22*, 3939–3964.
97. Van Elle Smartfoot Brochure.pdf.
98. Vroom Pre-fab foundation beams - Vroom Foundation Technology Available online: http://www.vroom.nl/en/products/5-pre-fab-foundation-beams (accessed on Sep 15, 2017).
99. WIPO Prefab in History Available online: http://www.prefabaus.org.au/prefab-in-history/ (accessed on Sep 8, 2017).
100. WIPO WIPO - World Intellectual Property Organization Available online: http://www.wipo.int/portal/en/index.html (accessed on Sep 8, 2017).
101. Armadillo System - Make your home TCFree Available online: http://www.armadillo-system.com/ (accessed on May 24, 2018).
102. Bubble Deck - Lighter Flat Slab Technology Available online: http://www.bubbledeck-uk.com/download.html (accessed on Sep 8, 2016).
103. Heinze Cobiax Deutschland GmbH Available online: http://www.cobiax.com/technology (accessed on May 24, 2018).
104. Helixsteel Available online: http://helixsteel.com.au/ (accessed on Feb 10, 2017).
105. Holedeck - Product - Holedeck Available online: http://www.archello.com/en/embedded/architect-at-work/event/architectwork-lyon/product/holedeck (accessed on Feb 17, 2017).
106. RibRaft Floors | Foundations | Concrete Flooring NZ Available online: http://www.firth.co.nz/residential/foundations/ribraft/ (accessed on Dec 7, 2016).
107. Bergan, P. O. System of domes for use in molding concrete slabs 1972.
108. Downer, M. J.; Tanner, R. W. Rain water recycling system using the void spaces of pods forming a waffle slab 2008.
109. Firth Industries *Firth RibRaft TC3 Concrete Slab Floor*; 2013;
110. Gilpin, D. C.; Stiles, B. D.; Stiles, S. R. Concrete void forming method and device 2017.
111. Golledge, B. F.; GOLLEDGE, M. A.; GOLLEDGE, L. A. Slab construction 2014.
112. Gonsalves, M. Concrete slab foundation and method of construction 1996.
113. Gordon, M. B. Storage of water, rainwater or grey water or other liquids beneath a concrete floor slab 2007.
114. Inoue, K.; Inokuchi, H.; Ueda, T.; Doi, T. Plane lattice hollow concrete slab and cross arm brace 2005.
115. Jr, D. P. G. Insulated concrete slab assembly 1999.
116. Koukourou, P. S. Building foundation 1988.
117. Koukourou, P. S.; Bayetto, P. M.; others The waffle pod footing system. In *Fourth National Local Government Engineering Conference 1987; Preprints of Papers*; Institution of Engineers, Australia, 1987; p. 117.

 doi:10.20944/preprints201807.0441.v1

118. Lassen, J. o slashed rgen Element for use in making a reinforced concrete structure with cavities, filler body for making such an element, and method of making a reinforced concrete structure with cavities 1998.
119. Leonardis, N. Foundation form work 1989.
120. Lindsay, R. L. Under slab water storage 2006.
121. Macchi, A. J. Concrete floor and ceiling slab construction 1965.
122. Major, P. W.; Peake, A. T. Foundations 2003.
123. Miller, F. R.; Blundell, S. G. P. Concrete flooring 2016.
124. Millman, P. Bubble relief form for concrete 1987.
125. O'Grady, J.; Italiano, G.; Fry, D.; Boykett, R.; Darbyshire, P.; Ryan, C. Cavity Former 2008.
126. O'grady, J. F.; Italiano, G.; Fry, D. A.; Boykett, R. K.; Darbyshire, P.; Ryan, C. T.; The Australian Steel Company Cavity former 2005.
127. Peer, C. V. de Foundation construction 1995.
128. Pontarolo, V. Accessory for modular elements for the support and ventilation of crawl spaces, floor structures, floors or similar articles in the building field 2004.
129. Pontarolo, V. Modular element for crawl spaces and floor structures 2003.
130. Pontarolo, V. Modular element for the support and ventilation of floors 2000.
131. Rauenhorst, G. A. Hollow-core concrete slabs and the method of making the same 1979.
132. Smorgon, A.-T.; Manual, D. Your guide to faster floors Hume Slab. **1999**.
133. The Australian Steel Company Cavity former 2005.
134. Swinimer, K. Footing form 2005.
135. Wells, D. Footing form 2003.
136. Vodicka, D. A. Prefabricated pier system 2002.
137. Butler Jr, R. P. Prefabricated concrete footings 2000.
138. Gerszewski, M. Precast concrete foundation elements and system and method of using same 1990.
139. Marquart, C. M. Prefabricated home foundation skirt system 1987.
140. Higuchi, T. Method for forming a continuous footing with prefabricated footing blocks 1979.